SCIENTIFIC
INSTRUMENTS

SCIENTIFIC INSTRUMENTS

Described by Specialists
under the Editorship of

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PREFACE

The complexity of modern science and the enormous range of modern knowledge have sometimes unfortunate consequences. One of these is specialisation, a result of which is that one group of scientists does not know how another group works. It often happens that one scientist would like to know something of the fundamental principles and uses of the instruments used by his colleagues, possibly in the hope that they may be helpful to him—or just to satisfy a commendable curiosity; this book is an attempt to meet this desire.

Scientific instruments are here described in a way that may be understood by the non-specialist so that the worker in one field may get a useful idea of the instruments used in another. The book does not set out to tell the specialist about his own equipment but about the other man's. The surveyor will not learn from it all that he ought to know about the theodolite and its use, but he may gather some useful information about calculating machines and lenses, while the mathematician and the optician may well like to know something about the theodolite or the mariner's compass which this book can tell them, though it will not tell them anything that as specialists they should know already about the slide rule and lenses, respectively. But how many of the vast numbers of people who every day use optical instruments—whether cameras or spectacles—understand the functioning of a lens?

The book is in no sense meant to be an exhaustive treatise on instruments, but it is hoped that it will be valuable to the student and to the research worker, as well as to many people who are using scientific instruments and require a working knowledge of them without going into the details of design.

As shown in the contents list, the book is divided into five sections of broad types of instruments and each section contains a chapter on various specific classes; thus Section 1, on optical instruments, has chapters on lenses, on microscopes and spectroscopes, etc.

Inevitably, selection and division of sections and chapters are somewhat arbitrary; thus the theodolite and sextant are described as surveying and navigational instruments but might have been included as optical, as indeed could the majority of scientific instruments. Any suggestions for rearrangement and indeed for any improvement in future editions will be welcome and careful consideration given to them. The Editor and Publishers are of course well aware that the book is very far from being exhaustive in the number of instruments it describes, but it is hoped that future volumes and editions will be justified by the reception accorded to this first effort.

Gratitude is expressed to all who have co-operated in giving advice and assistance, and to those specialists who have so kindly and carefully revised portions of the MS. and made valuable suggestions. The Editor feels particularly indebted to Mr. W. H. Johnson who first suggested the book and whose advice and assistance have been freely given throughout its preparation. Appreciation should also be expressed of the way in which the various authors have co-operated and helped each other.

So many firms and organizations have helped in providing information and illustrations that a separate list is appended, and to these also thanks must be expressed, for without their help the book would hardly have been possible.

January, 1946. HERBERT J. COOPER.

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Thanks are expressed to the following who have co-operated in the production of this book, in most instances by the loan of illustrations and in some cases by supplying useful information. Without their co-operation some chapters could not have been written but it should be emphasized that none of those mentioned is in any way responsible for the accuracy of any of the matter in the book.

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Chapter IX

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SECTION 1

OPTICAL INSTRUMENTS

CHAPTER I

LENSES

A lens is, in general terms, a piece of transparent refracting material designed to form images of objects placed so that pencils of light diverging from points of the object are, after refraction by the lens, made to converge toward or diverge from the corresponding point of the image. The relative distances and the relative sizes of the object and image are related to the focal length of the lens by simple formulae, and the focal length is related to the radii of curvature of the lens surfaces and the refractive index of the material. The lens surfaces are generally parts of spheres, but they may be aspherical or cylindrical and the lens itself is most commonly made of glass of optical quality, but progress is being made in the use of plastic materials with characteristics similar to glass. Lenses, either by themselves, or in combination with other lenses, prisms, mirrors, etc., are used in large numbers of scientific instruments and they are, of course, essential to most optical instruments. In this chapter it is proposed to describe briefly the various forms which lenses take and to discuss the defects to which they are subject so that the application of lenses to scientific instruments in general may be properly understood.

Historical

In very ancient times glass globes filled with water were apparently known, and the early development of lenses is shrouded in mystery, but they were mentioned as early as the 13th century in the writings of Roger Bacon. Their first use was, as far as can be ascertained, as burning glasses and later for spectacles and magnifying glasses, but their image forming properties must have been observed at an early date, and, in his *Magia Naturalis*, published in 1558, Giambattista della Porta mentions the camera obscura and the uses of mirrors and lenses. In 1608 Hans Lippershey, a Dutch spectacle maker, described a telescope which was also invented at about the same time by Galileo. In 1758 Dolland of London was the first to construct an achromatic telescope objective using a combination of two lenses of crown and flint glass. Since that time progress in the design and manufacture of lenses of all kinds has been comparatively rapid. Camera lenses became necessary from 1840 onwards, and because of the new problems arising from wide fields of view, it was at this time that most progress in the theory of lenses was made. Much theoretical work on lenses and the formation of images was done by Airy, Coddington and other British scientists but the first really co-ordinated system of geometrical optics was due to Gauss, who described the formation of images in optical instruments, and to von Seidel, who discussed the defects of the image. It is to Germany also that we must give the credit for the development of optical glass of types specially intended for lenses, although it can safely be said that British optical glass and British design work are the best in the world.

Raw Materials and Manufacture

The manufacture of optical glass is a highly-specialised trade involving the careful selection of materials and regulation of temperatures. The glass itself is usually made in "pots" of fireclay, each pot furnishing a so-called "melt" with definite characteristics as regards refractive index and dispersion. Glasses are described according to their types as Crown, Flint, Barium Crowns and Flints, Borosilicate Crown, Extra Dense Flint, etc., and are listed according to their refractive index and dispersion. The following table shows some characteristic types, and it will be noticed that in the "old" glasses the V-value, which is the reciprocal of the dispersive power, decreases as the refractive index increases, while in the "new" glasses we have types in which the high refractive index corresponds to a high V-value or low dispersion. This important distinction has considerable bearing on the design of lenses, and it was these "new" glasses which were originally developed at Jena in Germany.

Table
Representative Types of Old and New Glasses

Old Glasses	*N*	*V*	*V/N*
Hard Crown	1.5175	60.5	39.9
Extra Light Flint ..	1.5290	51.6	33.8
Light Flint	1.5746	41.4	26.2
Dense Flint	1.6041	37.8	23.5
Extra Dense Flint ..	1.7402	28.4	16.3
New Glasses			
Barium Flint	1.6530	43.2	27.9
Light Flint	1.5674	43.6	27.9
Dense Barium Crown ..	1.6098	53.3	33.1
Extra Light Flint ..	1.5290	51.6	33.8
Dense Barium Crown ..	1.6016	59.9	37.3
Telescope Flint	1.5151	56.4	37.2

The glass from the pots is allowed to cool slowly and is then broken up into lumps from which are moulded the lens blanks supplied to manufacturers. The lens blanks are made as nearly as possible to the size and weight required by the lens manufacturer so that the amount of "roughing" necessary will be reduced to a minimum. The lenses are ground to shape on special machines, on tools of many types, usually spherical cups, using emery of fine grades and finally rouge for polishing. The accuracy of the surfaces so obtained is tested by placing the newly-made surface in contact with a glass test plate whose curvature is accurately known and the discrepancies noted by the appearance of the interference fringes known as Newton's Rings. In optical instruments the lenses are carefully mounted and centred, the distances between the components being an important part of the design. On this account it is most unwise to take an optical instrument to pieces for cleaning unless it is certain that it can be reassembled exactly. The surfaces of lenses should not be touched by the fingers as the grease marks left are difficult to remove. Excessive rubbing must be avoided and soft-boiled linen is the best material to use for cleaning, moistened only with a little benzol or methylated spirit.

Types of Lenses

Simple lenses and the simple components of compound lenses are found in a variety of shapes which are illustrated in Fig. I. 1, the dotted pairs of lines in each diagram show roughly the position of the so-called principal planes. The principal foci of the lens are situated at equal distances from these planes when the lens is in air, and in calculating the distances of object and image by the elementary Gaussian formulae these distances must be measured from these planes. If the lens is considered as "thin" the two planes coincide.

For most purposes, other than in spectacles, lenses are not used singly but in combination with other lenses to form compound systems. Sometimes they are balsamed together to form doublets or triplets or they are spaced in mounts and are invariably associated with a stop or diaphragm which plays an important part in the construction. The reason for the use of these complex lens systems will be at once apparent if an attempt is made to use a single lens say as a telescope objective or eyepiece, or as a microscope objective, or a camera lens ; the image formed will be found to be so defective as to be quite useless. The defects of the image are due to the aberrations resulting from the refractions at the lens surfaces. It is most instructive to study the aberrations by examining the image formed by a simple bi-convex lens, using as object a grid of lines in two directions forming a series of squares or any conveniemt light source. For the lens a spectacle lens wlll serve provided it is of reasonably short focal length, and the image should be examined on a white card.

Defects of the Image

When an attempt is made to form an image with the object situated exactly on the axis it will be found difficult to decide where the best definition is obtained ; the image will be slightly fuzzy and surrounded by a sort of halo. This defect is due to *Spherical Aberration,* which can be defined as the failure of the light passing through the outer zones of the lens to come to the same focus as the light passing through the central zones. It will be found that the image can be made sharper by stopping down the lens so as to reduce the aperture, but no difference will result from moving the stop along the axis. It will also be noticed that the image will be coloured. As the screen is moved farther away from the lens there may be a red central dot surrounded by a greenish fringe edged with violet, and as the screen is moved towards the lens the centre becomes violet and the fringe reddish. This axial colour effect is due to *Chromatic Aberration* and is caused by the differences of the refractive index of the glass for different colours. In general the violet light is bent much more than the red light so that the image of a point source on the axis will be in the form of a spectrum with the violet end nearest the centre of the lens.

The spherical aberration and the chromatic aberration of a concave lens are in the opposite sense to those occurring with a convex lens, so by using two types of glass in combination it is usually possible to construct a lens consisting of convex and concave elements such that the spherical aberration and the chromatic aberration are removed for any given zone of the lens and for any given pair of colours, and very much

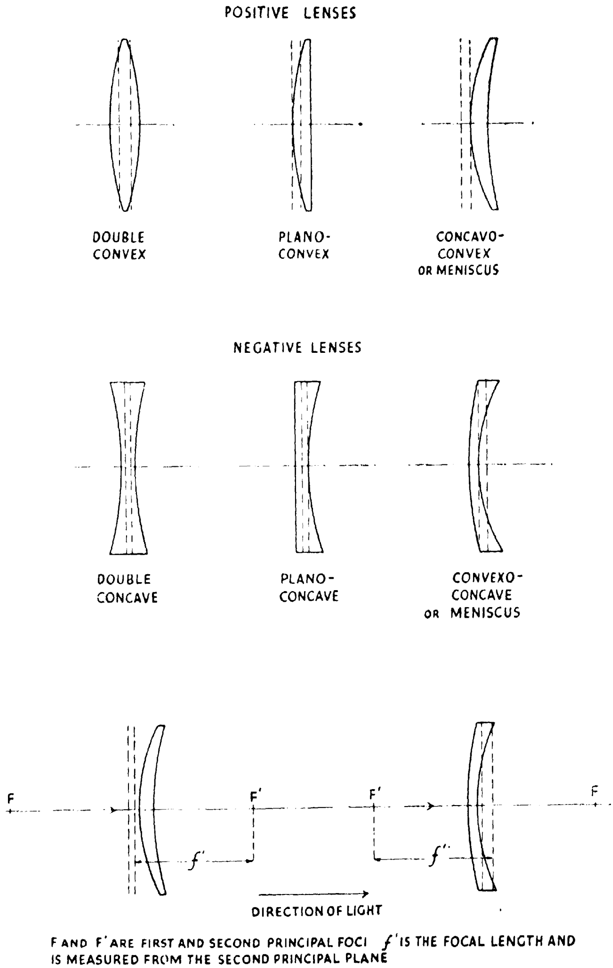

Fig. I. 1. Forms of lenses. The dotted lines indicate the positions of the principal planes.

reduced in general over the whole lens. Such a corrected lens is known as an achromatic doublet.

If now the lens is slightly tilted so that the object is no longer on the axis it will be found almost impossible to form any semblance of an image. The complex appearance which the image will take is caused by a combination of a number of aberrations, which, for convenience of

study are known as *Coma*, *Astigmatism* and *Transverse Chromatic Aberration*. It will be found that these transverse aberrations are very sensitive to the position of the stop and the shape and position of the image will change as the stop is moved along the lens axis.

In an attempt to form an image by moving the screen to and fro, it will be seen that when the screen is nearer the lens the image will be drawn out into an elongated form tangential to an imaginary circle drawn about the lens axis and that lines in the object in this direction are reasonably sharp, but much elongated. As the screen is moved away from the lens the image will contract in length and fatten out until it is roughly circular but very fuzzy and on still further withdrawing the screen the image will again be elongated but this time in a radial direction. This defect is due to *astigmatism*, which simply means the failure of the light to form a point image. Stopping the lens down has no effect on the distance between these two elongated images, but moving the stop has, and if lenses of different shapes are tried it will be found that the amount of the astigmatism will change. All the astigmatic images which have been examined will have been found to be associated with a halo or fuzz in one direction, rather like a brush or the tail of a comet, which will be reduced by stopping down and also by moving the stop. This defect is *Coma*, which is defined as the failure of the lens to form an image of the calculated size for all zones of the lens. In an achromatic doublet the coma can be reduced by a careful choice of glasses, and a coma-free doublet is often spoken of as an *aplanat*. Telescope objectives are an important example of a type of lens which is designed to be as free as possible from spherical aberration, chromatic aberration and coma. When the astigmatism is corrected as in photographic lenses the lens is frequently called an *anastigmat*.

No mention has yet been made of transverse chromatic aberration or chromatic difference of magnification as it is frequently called, but this defect is almost self-explanatory and is noticed as a colour fringe particularly when examining an object with a magnifying glass ; it is simply caused by the failure of the lens to form images of the same size for each colour of light.

In addition to the aberrations which have been described it will be found, if an extended object is used, that it will be generally impossible to find a position of the screen for which the whole image will be in focus; this is of course due to *curvature* of the image. Assuming that the best image will be formed at the point between the two astigmatic line images where the circular patch was found, it is obvious that the only way to alter the curvature will be by altering the astigmatism, but even if the astigmatism could be entirely removed the best images will still be formed on a curved surface, and moreover, no changes in the shape of the lens will in any way reduce this inherent curvature which depends only on the focal length and the refractive index of the glass. This inherent curvature is called the *Petzval curvature* of the lens, but the best image will only be formed on this Petzval surface if there is no astigmatism. Finally, it will generally be found that the image also suffers from *distortion*, a defect which is very sensitive to the position of the stop. In photographic lenses the elimination of distortion is considered of the utmost importance, for otherwise it would be quite

impossible to obtain good photographs of buildings and in fact, cheap cameras, in which single lenses are used, have so much distortion that architectural subjects cannot be photographed with any real success.

From the foregoing it should be quite obvious that the design of lenses for optical instruments is no simple matter, and lens design, in fact, is a highly-specialised business. The elementary formulæ found in text books on light are of no value whatever and unfortunately there is no compact and logical algebra available to the designer. The work consists in gaining experience from successful attempts and the laborious tracing of rays by trigonometrical computation, repeated trial and error and a final compromise. The possible combinations of curves, air spaces and glasses is almost infinite, but rough guides and experience can be used to curtail to some extent the early parts of design work. In the following paragraphs will be found a short description of some of the actual forms of simple and compound lenses.

Spectacles

The lenses used in spectacles for the correction of defective eyesight form a good example of the use of thin single uncorrected lenses, but even in spectacles the shape is of importance and in recent years contact lenses have been produced which are fitted directly to the front of the eye. Convex lenses are used for the correction of long sightedness, concave lenses for short sight, cylinders for astigmatic eyes and prisms to correct any lack of parallelism in the eyes. Spectacle makers usually stock large quantities of half-finished lenses, ground to various shapes on one side and with the other side ready for finishing to any curve, cylinder or prism, according to the optician's prescription. The power of spectacle lenses is always quoted in *dioptres*, one dioptre being the power of a lens of one metre or forty inches focal length, and power being defined as the reciprocal of the focal length. Thus the power of a lens in dioptres is equal to 40 divided by the focal length in inches. Spectacle lenses may be double convex or plano convex in shape, but it is more usual and better to fit "periscopic" or meniscus lenses to spectacles because the correction is then better over a wide field. Meniscus lenses are shown in Fig. I. 1, and the periscopic type are of shallow meniscus form, the curvatures being standardised for ease of production.

Magnifying Glasses

The simple magnifying glass or reading glass of moderate power is so familiar that no description is necessary, but where more power is required for greater magnification it is soon found that the simple lens is no longer adequate. Distortion and chromatic effects are the two main defects which become apparent as soon as high degrees of magnification are used. Ordinary high power magnifiers for dissecting work and other special purposes are often sold in the form of achromatic doublets of plano convex shape and such lenses should be held with the plano side nearest the object if the eye is far away from the lens, but with the convex side nearest the object if the eye is held close to the lens. The inconvenience of having to turn the lens over to find the correct way of using it is removed by the use of an achromatic triplet first made

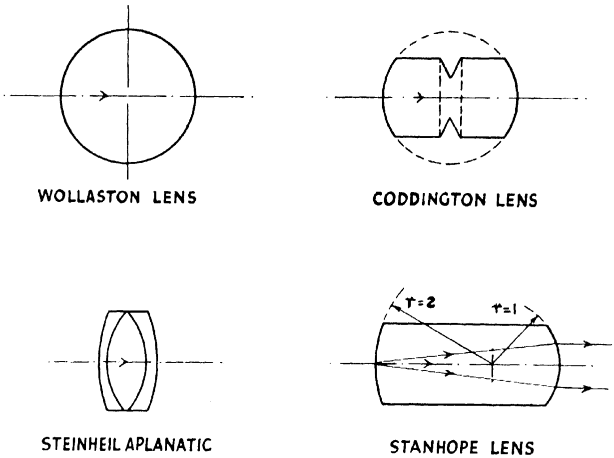

Fig. I. 2. Magnifying glasses. Some special forms of magnifying glasses. Simple lenses are also used for this purpose.

by Steinheil and shown in Fig. I. 2. The Wollaston and Coddington lenses were attempts to eliminate colour effects with the use of only one glass but they have curved fields which are troublesome. The Stanhope lens is much used in very minute form in which a picture, usually advertising some resort is transferred on the less curved surface and is seen highly magnified when the eye is placed close to the other side.

The magnifying power of a lens is usually defined as the ratio of the size of an image formed by the lens at the least distance of distinct vision (10 inches) to the actual size of the object and the magnifying power is thus equal to 10 divided by the focal length in inches, or the power in dioptres divided by 4.

Telescope Objectives

It has already been said that for a telescope objective to be of any value it must be achromatic and free from spherical aberration and coma. For small telescopes, up to about 2 inches in diameter, these conditions can be reasonably easily fulfilled by a cemented doublet consisting of a hard crown and a dense flint glass, but where larger diameters are required the pair of lenses forming the doublet are seldom cemented and may be of the type shown as the Fraunhoffer objective in Fig. I. 3. The Gauss type of telescope objective, frequently fitted in large theodolites, is designed to be free from spherical aberration for two colours, thus giving very good definition for very small objects on the axis. For astrographic purposes, where it is important to be able to focus visually and then to photograph a star, the Cooke photo-visual objective is invaluable and for general astronomical photography where a comparatively large field is required, a photographic objective such as the Tessar type is often used.

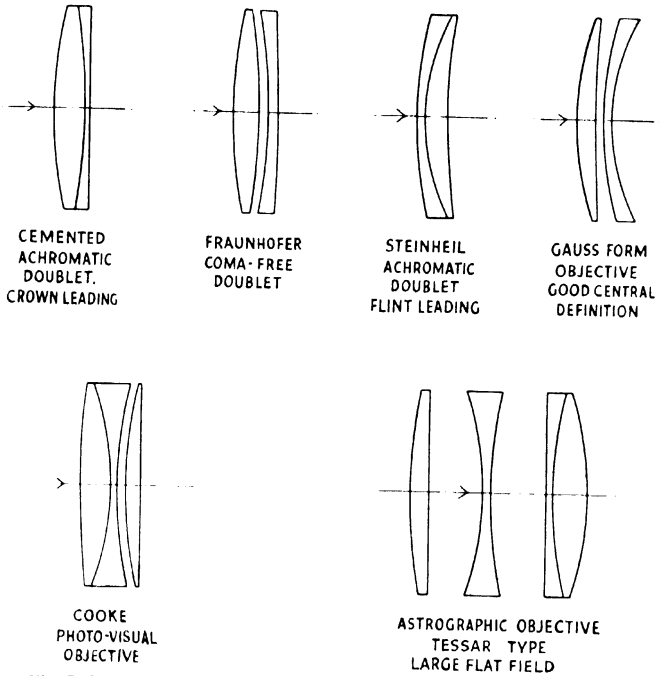

Fig. I. 3. Telescope objectives. These are typical forms; many other types are used.

The manufacture of large diameter telescope objectives is a specialised trade and great care has to be taken to ensure that the glass discs are free from flaws and very thoroughly annealed. After the lenses have been ground and polished to the calculated curvatures it is always necessary to work on the lens by hand, figuring the surface as it is called, to remove irregularities due partly to errors in curvature and partly to lack of homogeneity in the glass.

Microscope Objectives

In order that minute objects may be enlarged very greatly to make them visible, the microscope objective is a lens of very short focal length, placed close to the object so that an enlarged primary image is formed at a standard distance behind the objective. This enlarged image is further enlarged by the eyepiece and the magnification of the whole instrument is the result of the combined magnifications of the objective and the eyepiece. The standard distance at which the image is formed is called the "tube length" for which the objective is designed. Some typical microscope objectives are shown in Fig. I. 4. In the Lister type of objective use is made of the principle that there are two pairs of points associated with a corrected lens for which the spherical aberration is least.

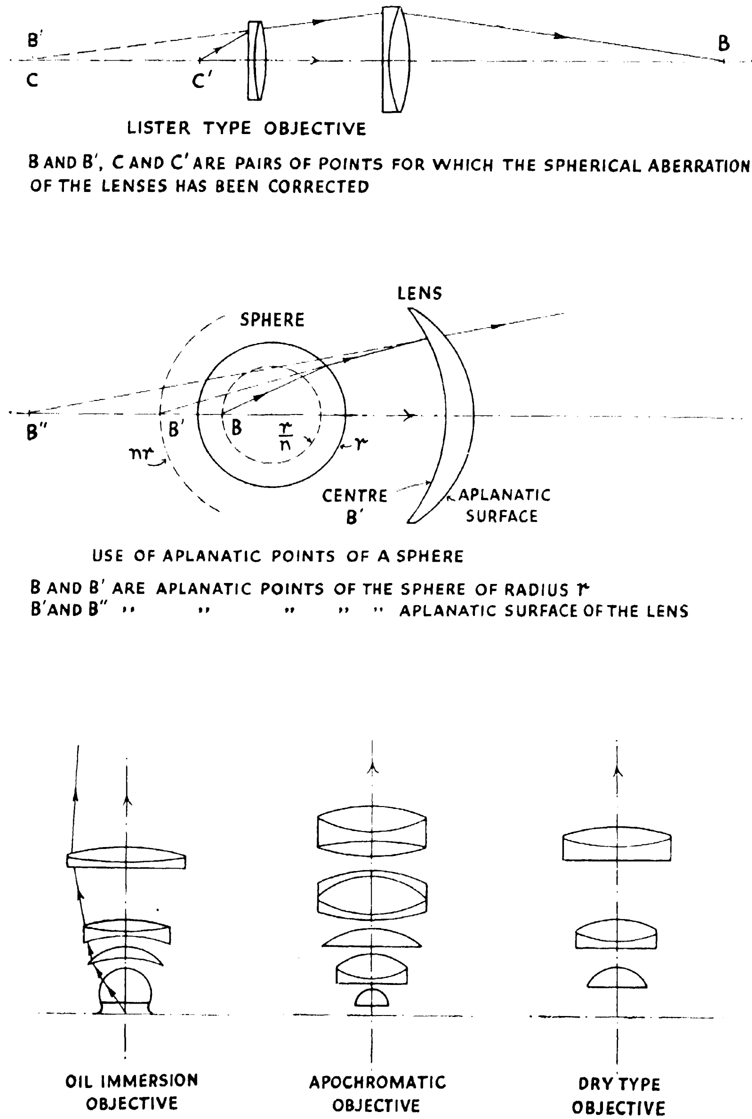

Fig. I. 4. Microscope objectives. The principles of Lister and of the aplanatic points are much used in microscope objectives and their applications can be seen in the typical forms shown. Many other types are, however, used.

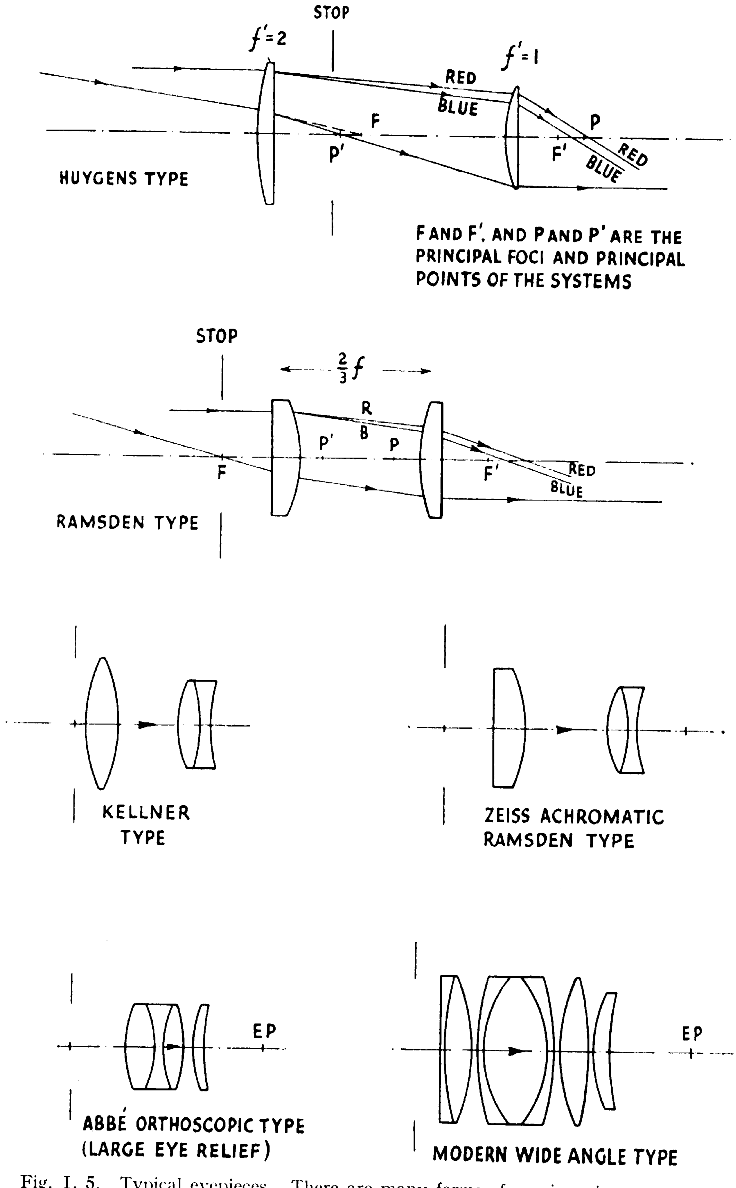

Fig. I. 5. Typical eyepieces. There are many forms of eyepieces in general use. The Huygens type is common in microscopes and the Ramsden type in telescopes.

In the immersion types of objectives the principle of the existence of the aplanatic points of a sphere is used. These points are such that all light diverging from one point appears to diverge accurately from the corresponding point after refraction. The first of these points is within the sphere, and since this point is inaccessible, the sphere is flattened and a drop of cedar oil is placed between the flattened portion and the object. Cedar oil has very much the same refractive index as glass and thus the object point is virtually embedded within the sphere at the required point.

Apochromatic objectives are designed to be free from chromatic aberration over a large range of colours, and frequently fluorite is used in their construction, but these objectives usually have to be used with compensating eyepieces because they suffer from chromatic difference of magnification.

Eyepieces

Fig. I. 5 shows some typical forms of eyepieces. The Huygens eyepiece is largely used in ordinary microscopes and in a number of telescopes and is an example of the lens system which can be made achromatic by spacing two lenses of the same glass at a calculated distance. In the Huygens eyepiece the focal plane lies between the lenses, but in the Ramsden type, which is also achromatised by separation, the focal plane is in front of the field lens and is thus accessible for cross wires or graticules. In modern eyepieces, the component lenses are usually in the form of achromatic doublets or triplets, a complication which has been imposed by the demand for wider apparent fields of view.

Camera Lenses

Camera lenses differ from most other forms of lenses in that they are intended to form images on comparatively large flat surfaces, i.e., they have a flat field and a large field. It is therefore clear that a camera lens should be as free as possible from curvature of field, astigmatism and coma as well as colour magnification; it should also be free from distortion, but a little spherical aberration can be tolerated as the grain of the photographic emulsion does not permit of the resolution of the finest detail.

Simple meniscus lenses are used in huge quantities in the cheap cameras and the average type of amateur camera seldom rises above a simple double lens, which may be of the so-called R.R. type. In the R.R. lens use is made of the symmetrical construction to eliminate as far as possible the effects of the oblique aberrations. The introduction of the new Jena glasses enabled considerable advances to be made in the design of camera lenses and recently the introduction of some rare earth glasses has led to a number of new designs in which better corrections can be expected. The anastigmat type of lens largely found in the better cameras and used by professional photographers may take many forms, one of the commonest being the Tessar type. Fig. I. 6 shows a number of typical lens constructions but it is obviously impossible to discuss the merits and performance of these lenses in the scope of this chapter.

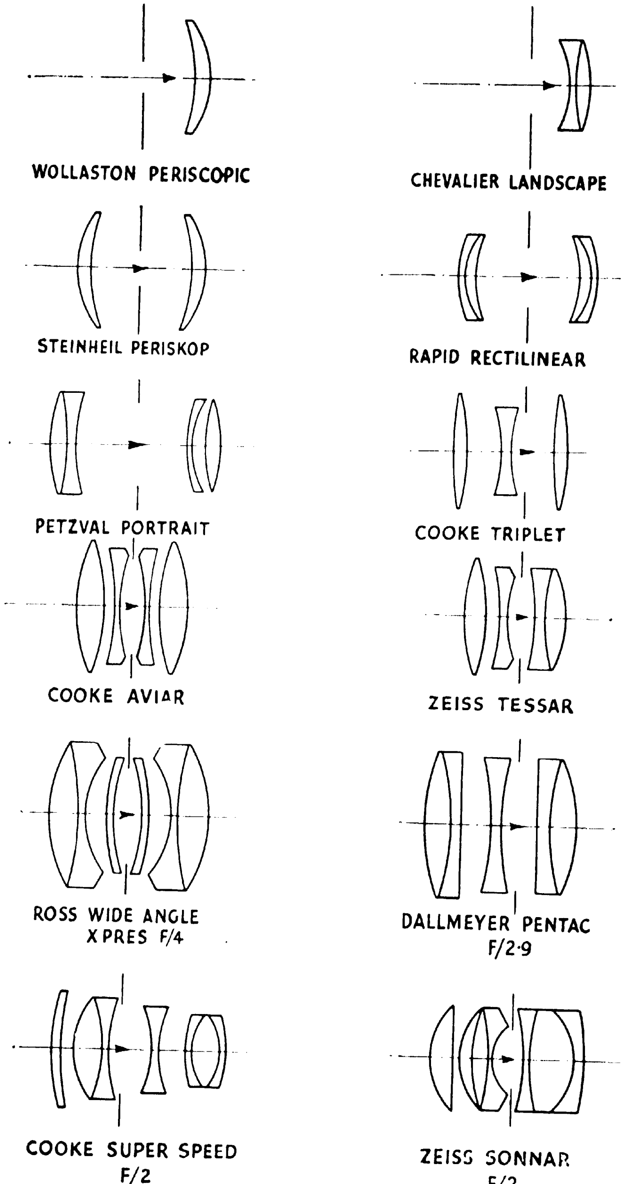

Fig. I. 6. Typical photographic lenses. The Wollaston and Steinheil types are much used in cheap cameras, the Tessar and Aviar types are very common in better cameras.

The reader is referred to the following books on Optics generally and to articles in the various editions of the *Encyclopedia Britannica* for fuller information.

Elementary Text Books :
Edser—*Light.*
Martin—*Applied Optics.*
Houston—*Light.*
Steinheil & Voit—*Applied Optics.*
Cox—*Optics* (*Camera Lenses*).

More Advanced Text Books :
Heath—*Geometrical Optics.*
Herman—*Geometrical Optics.*
Drude—*Optics.*
Conrady—*Applied Optics.*
Steward—*The Symmetrical Optical System.*

CHAPTER II

CAMERAS

A camera is an instrument by which a permanent record is made of the image of an object formed by a lens. The image is recorded on a piece of material which is sensitive to light and is called the negative material; it consists of an emulsion of silver bromide in a solution of gelatine, which is coated on a transparent base. When glass is used for the base, the negative material is called a plate. When a flexible material is used it is called a film. Nitrocellulose, which is highly inflammable, and cellulose acetate, considerably less inflammable, are the most commonly used film materials.

When the negative material is exposed to light the silver bromide undergoes a change which is not immediately visible, and a latent image is said to exist. By development of the negative, the light-affected silver bromide is transformed into metallic silver and the image becomes visible, then being made permanent by a process called fixing. The negative does not give a true record of the object photographed, as the light values are reversed, a light part on the object appears dark on the negative and vice-versa. By exposing a piece of sensitive paper to light through the negative, the light values are again reversed and a photograph with similar light values to the object is obtained.

Shutters

The brightness of the object being photographed, the sensitivity of the negative material, or the speed with which it reacts to light, and the amount of light allowed to pass through the lens, are determining factors in the length of time for which the negative material must be exposed. Hence a camera must include a device, called a shutter, for regulating the time of exposure. There are two types of shutters commonly used, diaphragm and focal plane. A diaphragm shutter is placed between the elements of the lens, and consists of a number of thin metal leaves which can close in to form a perfect light shield, or open to allow the full passage of light through the lens. The time for which the shutter remains open is spring controlled and can be adjusted to give a range of times. The focal plane shutter is placed directly in front of the negative material, and consists of a blind of opaque cloth which contains a slit of adjustable width so that as the blind passes across the negative material the amount of light reaching it is controlled by the slit width. A double blind makes the slit width more easily variable and is generally used. The shortest possible exposures are about 1/500 second and 1/1,000 second with the diaphragm and focal plane shutters respectively. An important means of obtaining a very short exposure, not possible with a mechanically-operated shutter, is by use of the spark discharge of an electric condenser in a gas-filled tube, which can be made to give a very high power light flash of very short duration, 1/1,000,000 second being possible. This renders a fast shutter unnecessary, the exposure being controlled by the time of the flash.

Focusing

As explained in the chapter on lenses, an object at an infinite distance from a lens forms an image at a distance from the lens which is called the focal length, and as the object approaches the lens, so the image recedes from it. A focusing device allows the distance between the lens and the negative material to be adjusted so that objects at varying distances can be photographed. Correct focusing entails movement of the lens backwards or forwards by means of a screwed lens mount or leather bellows, and correct positioning of the lens so that the image is formed at the correct distance from it. The following methods are commonly used :—

(a) By inserting a ground glass screen in the place of the film or plate and adjusting the position of the lens until a sharp image is formed on the screen.

(b) By rangefinder. When the rangefinder is "uncoupled," the distance of the object from the lens is determined by the rangefinder, and the position of the lens is adjusted against a distance scale. When the rangefinder is "coupled," the action of setting the rangefinder is conveyed to the lens which is automatically positioned correctly.

(c) By a reflex device. A mirror is contained in the body of the camera, between the negative material and the lens, and is set at 45° to the lens axis. This mirror intercepts the light rays passing through the lens and reflects them on to a ground glass screen on the top of the camera, the position of the screen being such that each light ray travels the same distance from lens to screen as from lens to negative material with the mirror removed. Focusing is carried out on this screen. When an exposure is made a mechanism lifts the mirror just prior to the opening of the shutter. A twin lens "reflex camera" consists of two compartments, the lower compartment housing the photographing lens and negative material, and the upper compartment housing a focusing lens, a mirror set at 45° to the lens axis, and a focusing screen. The image is focused on the screen, during which process any movement given to the focusing lens is also given to the lower lens, the two lenses being coupled together.

In the focusing method (a) the image is seen the same size as it will ultimately appear on the negative, thus affording a means of positioning and composing the picture, with the disadvantage of the image being upside down and reversed sideways. The focusing screen on a reflex camera can likewise be used as a viewfinder, and in this case the mirror rectifies the image and it is seen the right way up. A camera which focuses by rangefinder must be supplied with a separate viewfinder. Most focusing screen and reflex cameras are provided with an auxiliary viewfinder.

Lens Apertures

The effective lens area, through which light is allowed to pass is made variable in order to give a further control over exposure time, and also to control depth of focus. If a negative is made with a given lens, and then the lens is stopped to one-half its original diameter, the effective lens area will be reduced to one-quarter the original area, and the exposure required to give a similar negative will be four times the original exposure.

Now consider two lenses of different focal lengths, one twice the other, the effective lens diameters being equal. To obtain negatives of equal density with the two lenses from the same object, the exposure with the longer focal length lens would have to be four times the exposure with the shorter focal length lens, as the image areas would be in the ratio of 4 to 1. The aperture of a lens, denoted by f, is defined as the ratio between the focal length and the lens diameter, and exposure times are proportional to f^2. Thus a lens stopped to $f/6$ would require four times the exposure as when stopped to $f/3$. A stopping device in a camera in the form of an adjustable iris diaphragm between the lens elements is set to a scale marked with the f number. A scale in common use is marked $f/2$, $f/2.8$, $f/4$, $f/5.6$, $f/8$, $f/11.3$, so that stopping down to the next number entails doubling the exposure.

Another effect of stopping down a lens is to increase the depth of focus. Supposing a lens of 2 in. focal length and stopped to $f/4$ is focused on an object at a distance of 20 feet from the lens, it would be found that all objects between 15 feet and 30 feet from the lens would appear equally sharp on the negative. In this case the depth of focus is $30 - 15 = 15$ feet. If the same lens is now stopped to $f/8$, the depth of focus increases, and all objects between 12 feet and 53 feet are equally sharp. Thus it can be seen that with a sufficiently small aperture the depth of focus could be increased to such an extent that all objects between, say, 6 feet and infinity, would appear equally sharp on the negative, and a focusing device would be unnecessary; such conditions hold with box cameras. The depth of focus decreases with (i) decrease of distance of object from lens; (ii) increase of focal length of lens, and (iii) decrease of f number. Hence the majority of cameras suitable for serious work must be provided with a focusing device.

PROJECTORS

A projector is an optical instrument which is used to produce an enlarged image of an object. The image is projected on to a screen and the object might be a lantern slide, positive film, microscope slide, or an entirely opaque object, in which case the profile of the object will be produced on the screen as the boundary line of the projected shadow. The production of a glass slide or a positive film, from a negative, is a similar process to the production of a photograph from a negative, but in the case of cine-films the positive is sometimes produced by treatment of the negative material, which is then called reversal film. Colour films are processed so that a positive, or colour transparency, is produced by treatment of the negative material, and projection is the most satisfactory way of viewing a colour transparency.

The optical system of a still projector, as distinct from a cine-projector, is simple, and consists of the following items: a high-power projection lamp; a light reflector, used to conserve as much of the light as possible; condenser lenses for concentrating the light rays; and a projection lens. The object for projection is placed between the condenser lenses and the projection lens. This optical system must be suitably housed, and means provided for adequate ventilation, as the

high-power projection lamp is liable to produce much heat. Such an instrument for projecting transparencies is sometimes referred to as a diascope. 35 mm. positive film provides a very convenient medium for making a series of pictures for projection. The film is kept in a roll and a special carrier is used in which the film is wound from one spool to another as each picture is projected, the film being held flat between two glass plates during projection.

PROFILE PROJECTOR

A profile projector (Fig. II. 1) is a highly accurate instrument and is used for checking the shape and dimensions of the profile of such objects as plate gauges, screw threads, templates, and cams; and in conjunction with a surface illuminator can be used for checking surface dimensions and inspecting surface characteristics. The optical system is essentially the same as for the ordinary still projector except that it is most essential that the condenser produces a parallel beam of light rays, and in some designs a water cell is inserted between the condenser and the object for the purposes of preventing heat from the projection lamp from reaching the object. The positioning of the parts and object is very critical, and the complete instrument is usually designed so that the screen is in close proximity to the optical equipment. A known accurate magnification of the object, such as 50 or 100 times, is obtained according to the focal

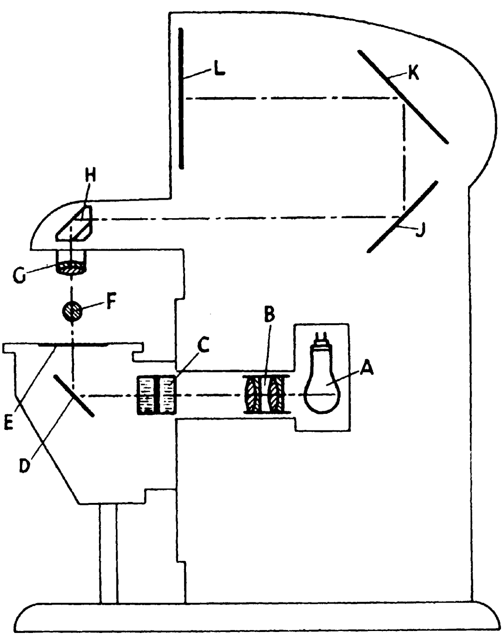

Fig. II. 1. Bausch and Lomb profile projector.

A. Projection lamp
B. Achromatic condensers
C. Water cells
D. Mirror
E. Glass stage plate
F Object
G. Projection lens
H. Roof prism
J. Mirror
K. Mirror
L. Screen

length of the projection lens, and the distance between the screen and the lens, and the image is checked against a master profile accurately drawn to the same magnification on a base not affected by changes of temperature and atmospheric conditions. With the object of improving definition the following procedure is advised with the Hilger projector. A green light filter is placed over the lens, which gives a green background on the screen, and the master profile is drawn with red translucent ink on kodatrace. This drawing is mounted between two sheets of glass, which forms the screen on to which the image is projected. Such a screen is called a book screen.

A plain ground glass screen is used for the projection of surfaces. Master profiles and dimensions can be drawn on such a screen with pencil which will wash off after use. A protractor screen consists of a fine ground glass screen mounted in a ring graduated in degrees and provided with etched reference lines, and it can be rotated in the ring. A vernier enables angles to be measured to a fine degree of accuracy. A photographic plate holder can be substituted for the screen, so that permanent records can be made.

EPISCOPE

An episcope produces an image by reflection from the surface of an opaque object. By its use enlarged reproductions can be made of illustrations, photographs, botanical specimens, surface patterns on wood and metal specimens, and similar objects. The optical system consists of a source of light directed on to the surface of the object. Light reflected from the surface is projected by a lens on to a screen. A platform is provided on which the object is placed and which positions the object correctly. It is essential that as much as possible of the available light is used to illuminate the surface, mirrors being employed for this purpose.

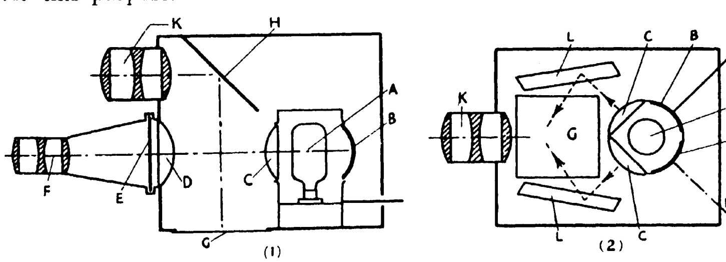

Fig. II. 2. Ross epidiascope. (1) Light rays direct from the projection lamp A, and reflected rays from the reflector B, are concentrated by the condenser lenses C and D, then pass through the slide E, the image of which is projected onto the screen by the projection lens F. G is the object for episcopic projection, H a mirror and K the episcopic lens. (2) This diagram is a plan view showing the episcopic illumination system. There are two reflectors B, and two condensing lenses C, in use, which direct the light rays onto two inclined mirrors L and thence onto the object G. For diascopic illumination the lever M is moved to the position M1, one reflector and one condenser lens then being used.

EPIDIASCOPE

An epidiascope (Fig. II. 2) is a compound instrument combining an episcope with a diascope (a projector). A common light source is used for both projection systems which can be used alternatively, selection being effected by the movement of a lever.

CINE-CAMERAS

The requirements of a cine-camera (Fig. II. 3) are similar to those of a still camera, with a number of important additions. Exposures must be made at the rate of 24 per second for sound films, and 16 per second for silent films. This means that the film must be fed to a position behind the lens and then held stationary whilst a shutter makes the exposure, all in 1/24 second. The film is drawn from the supply roll by means of a rotating sprocket wheel at a rate of 18 inches of film per second for 35 mm. film, the sprockets fitting into the perforations in the film, which is held against the sprockets by small rollers called sprocket idlers. The film is made to form a loop after leaving the sprocket wheel and is then passed behind the gate which is an opening the size of the required picture, and is situated behind the lens. Film is drawn from the supply roll continuously, but must pass the gate with an intermittent motion. Such motion is derived from a mechanism, a simple type of which is known as the Lumière claw mechanism, in which a claw is actuated so that it enters a perforation hole in the film, pulls the film down the required distance, and then leaves the hole, the film remaining stationary until the claw is in position for pulling down the next frame. The time taken for moving the film is about 1/72 second, and the film remains stationary for about 1/36 second. A more complicated form of this mechanism uses two claws, one for moving the film and the other for holding it stationary.

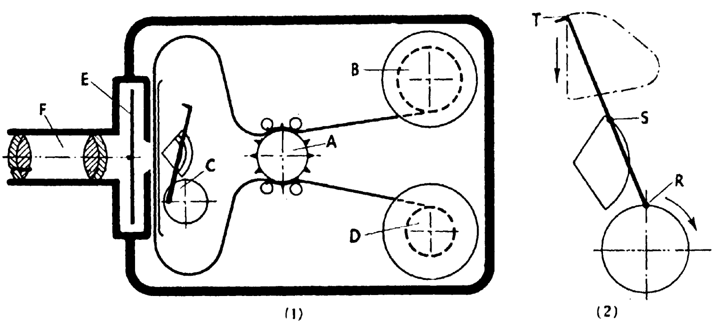

Fig. II. 3. Cine-camera. Diagrammatic representation. (1) The sprocket wheel A draws films from the supply reel B. The claw mechanism C pulls the film past the gate and the sprocket wheel feeds the film to the take-up reel D. E is the revolving shutter and F the lens. (2) The end R of the claw arm revolves in a circle. The point S moves round the cam profile and the claw T traces out the shown curve.

The exposure time is controlled by a revolving disc shutter, situated between the lens and the gate. The shutter consists of two flat circular discs each with a sector removed, hence by relative movement of the discs an open sector of variable angle can be formed. As the shutter revolves the open sector passes the gate at the time when the film is held stationary, and the exposure is made. It is obvious that the sprocket wheel, the claw mechanism, and the shutter must all be geared together in some way so that their movements synchronise. The maximum exposure time must be slightly less than the time for which the film is held stationary. A single disc with a fixed opening allows only one exposure time in which case the exposure is controlled by stopping the lens.

The film forms another loop after leaving the gate and then makes contact with the sprocket wheel which feeds it to the take-up reel.

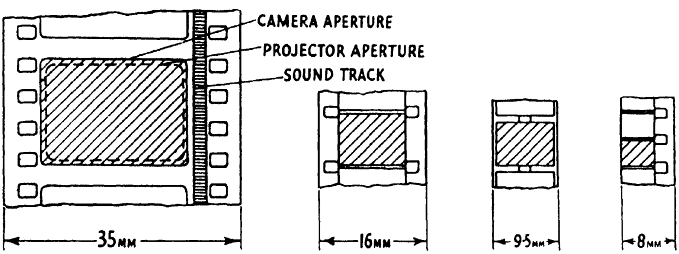

Fig. II. 4. Cine-film sizes. Diagram showing the relative sizes of 35 mm. sound film, and 16 mm., 9.5 mm., and 8 mm. silent film.

When the film has been exposed, it is developed and fixed to form a negative and then positives are printed from this negative on positive film. 16 mm., 9.5 mm. and 8 mm. (Fig. II. 4) films, which were introduced for amateur work, are processed after exposure so that a positive is directly produced. This process is cheaper than the production of a positive from a negative, and the film is called reversal film.

When a sound film is made the picture does not take up the whole of the available film width, a strip being left at one side of the picture for the sound track. The sound impression may be made at the time of making the picture either directly on the film, or on a separate negative from which it is printed on to the positive film ; or it may be made at some other time and synchronised with the picture when the positive is made.

CINE-PROJECTORS

The optical system of a cine-projector consists of a source of light, reflector, condenser and projection lens. The mechanism must provide a means of passing the film into the field of the optical system with intermittent motion at the same speed as the film is taken, and whilst the film is being moved past the projection gate, the light must be cut off from the projection screen. After passing the projection gate the

film must then pass through the sound gate where the sound track is converted to sound. It should be noted that this takes place 15 inches beyond the projection gate hence the sound track is displaced this distance from its accompanying picture.

The intermittent motion is produced by the Maltese Cross mechanism (Fig. II. 5). Whilst the film is being moved past the projection gate

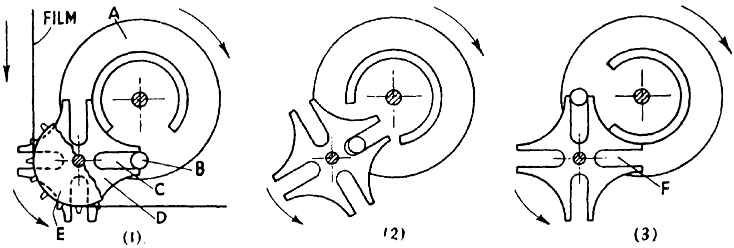

Fig. II. 5. Maltese cross mechanism. Position (1): The wheel A is revolving at constant speed and the pin B is just entering the slot C in the cross D. The film passes over a sprocket wheel E which rotates with the cross. Position (2) : The cross is being rotated and the film is being pulled past the projection gate. Position (3) : The pin is just leaving the slot and the cross will remain stationary until the wheel A has rotated another three-quarter revolution and the pin enters the next slot F.

the light is cut off by a shutter which is coupled to the Maltese Cross mechanism by a gear train to ensure perfect synchronism. The disc type shutter consists of a revolving flat circular plate with two diametrically opposite sectors removed, leaving two blades. One of these blades is called the master blade which cuts off the light whilst the film is being moved, the other is called the cut-off blade and its function is to adjust the relative periods of light and dark on the screen in order to reduce flicker. Another type, the horizontal cylindrical shutter, consists of a hollow metal cylinder with two diametrically opposite portions of the curved surface cut away for the whole length of the cylinder, leaving two blades. The cylinder revolves on its axis. This type of shutter reduces the time of cutting off light by one-half compared with a single disc shutter, by reason of the fact that as one blade is cutting down through the light beam the other blade is cutting up. The shutter is best positioned between the light source and the film for then only 50 per cent of the heat accompanying the light reaches the film.

The light source is either an electric arc, which is mostly used with large projectors ; or a filament lamp for small projectors. The mounting of a projector is very important, particularly if it has a large throw, because of the necessity of avoiding vibrations.

CHAPTER III

THE MICROSCOPE AND ELECTRON MICROSCOPE

The function of a microscope is to produce an enlarged image of a minute object, in order that its fine structure may be examined.

However this image is observed, whether directly through the instrument, or indirectly by a photographic reproduction, an image is finally produced on the retina of the eye which has a granular structure, like the grains of a photographic plate, or the small dots which form a newspaper photograph. This structure consists of a large number of minute light sensitive elements, the rods and cones, the distance apart of which is about 1/200 mm. Each rod and cone produces a separate visual sensation in the brain. It is clear that any detail in the object examined which produces an image on the retina smaller than this cannot be seen.

It is well known that as we bring an object nearer to the eye, it appears larger and more detail can be seen. This is clearly due to the increase in size of the retinal image. It is also a well-known fact that objects become blurred if brought too close to the eye. This is because the crystalline lens of the eye reaches its limit of refracting power for a normal eye for an object distance of about 10 inches or 25 cm., a distance known as the least distance of distinct vision, usually denoted by the symbol *D*. This implies that detail in the object less than about 0.2 mm. cannot be distinguished.

The Simple Microscope

This consists of a single convex lens, or lens combination which behaves as a convex lens, the purpose of which is to supply extra refractive power to the eye so that objects brought much closer than 10 inches can be properly focused on the retina. As a consequence an enlarged retinal image is formed, as if an enlarged object were placed at the near point of distinct vision, so enabling finer detail to be observed. Fig. III. 1,

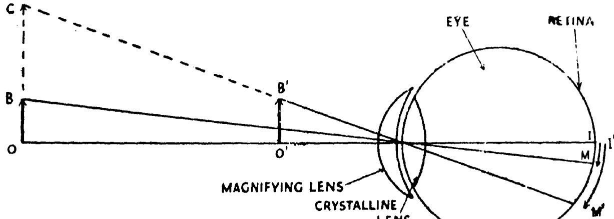

Fig. III. 1. Simple lens used as a magnifier. oB: Object at least distance of distinct vision (D), seen clearly by naked eye, producing image IM on the retina. I^1M^1: image of o^1B^1 on the retina formed with the help of the magnifying lens, such that oc is the apparent position and size of o^1B^1 as seen by the eye.

$$\text{magnification } \frac{I^1M^1}{IM} = \frac{oc}{oB} = 1 + \frac{D}{f}. \quad f = \begin{matrix}\text{numerical value of} \\ \text{focal length.}\end{matrix}$$

which is self-explanatory, indicates how the magnification is produced. This may be calculated from the formula $m = 1 + \frac{D}{f}$ where m = magnification, f = focal length of the lens.

A simple convex lens is only useful for small magnifications, say up to three times. For higher magnifications, because of the distortion and colour effects which a simple lens produces with white light a compound lens is used, consisting of lenses of different kinds of glass cemented together. A very efficient type, much used, called an Aplanatic is shown in Fig. III. 2, consisting of two concave lenses combined with a single convex. It is made with magnifications of from six to twenty times, is colour free and distortionless, and gives a wide flat field of view. With some slight sacrifice of these qualities, magnifying powers of up to a hundred can be obtained by other suitable combinations of lenses.

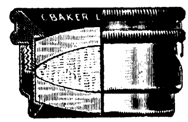

Fig. III. 2. Aplanatic lens.

For still higher magnifications, apart from the working distance being too small, it is impossible to correct adequately for colour and distortion. A magnifying power of a hundred represents the upper limit possible with the simple microscope.

The Compound Microscope

Magnification is produced in the compound microscope in two stages. This is illustrated in Fig. III. 3. The lens near to the object (the objective) produces a real magnified image, the magnification being given

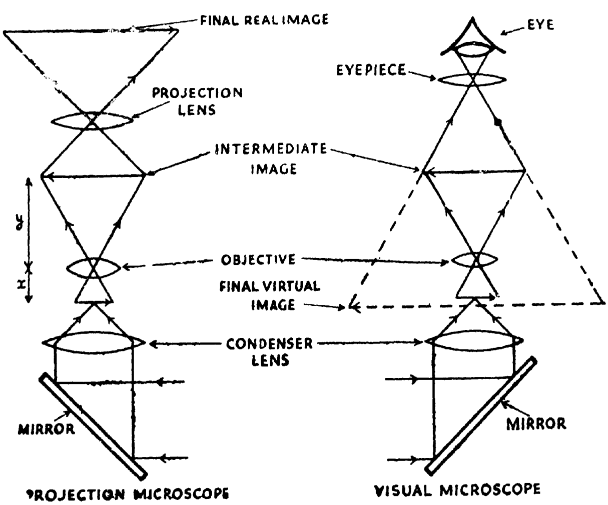

Fig. III. 3. Magnification by a compound microscope.

by the ratio y/x. In the visual miscroscope, this image is observed through the second lens (the eyepiece) which acts like a simple microscope, so that the final image is viewed as if it were at the least distance of distinct vision. In the projection type, the lens (the projection lens) throws the final magnified image on to a screen or photographic plate.

The tube length of a microscope (corresponding to y) is standardised at about 160 mm. The shortest distance x (corresponding to the focal length) is about 2 mm., so that the highest magnification produced by an objective is about 80. The highest powered eyepiece used in practice gives a magnification of about 15, so that the greatest overall magnification used is about 1200. Now this corresponds to a superficial magnification of over a million times, so that the illumination of the final image would only be a minute fraction of that of the object. For this reason it is necessary to provide concentrated illumination on to the minute object. This function is performed by the condenser, which focuses light from daylight or other source of illumination on to the object.

A linear magnification of about 1000 is the useful limit of magnification with the best quality microscope for the following reason. The mean wavelength (λ) of white light is about 6×10^{-5} cm. Theory shows that because of the wave nature of light, the least distance (R) between two points that can be resolved (i.e. distinguished as separate) by the microscope objective is given by $R = \frac{1}{2}\lambda/N.A.$ $N.A.$ is the numerical aperture of the objective, defined by $\mu \sin \alpha$ (Fig. III. 4), μ being the refractive index of the medium in which the object is immersed. Usually the medium is air in which $\mu = 1$, but in an oil immersion, or water immersion objective, μ is greater than 1. Since the least detail which the eye can detect is 0.02 cm., the microscope must convert a distance R into 0.02 cm. Thus the necessary magnification is $0.02/R = 2/3 \times 1000 \times N.A.$ No more detail is brought out by any further increase in magnification, no matter how large. (The reader will find it instructive to examine a newspaper photograph with a magnifying lens.) The highest numerical aperture theoretically possible is realized in an oil immersion objective at about 1.5, so that the highest useful magnification possible is about 1000. For ease of viewing, magnifications of up to 1500 are used, but there is no gain in resolving power.

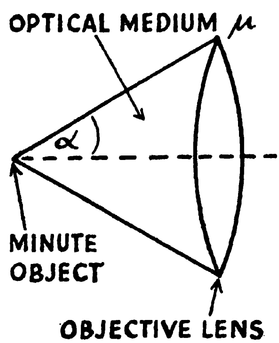

Fig. III. 4. Numerical aperture of an objective.

A good microscope can reach this theoretical limit because it is corrected for colour and distortion. This correction must be carried out for all three components, condenser, objective and eyepiece.

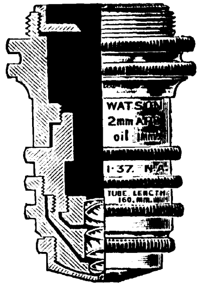

Fig. III. 5. Oil immersion microscope objective.

The Objective

Fig. III. 5 shows the construction of an objective of large *N.A.*, and consequently of large magnification. An achromatic objective uses crown and flint glasses, whilst an apochromatic uses fluorite in addition. The latter is more highly corrected for colour than the former, and is used in objectives of the highest power (4 mm. and 2 mm. focal lengths), in which the achromatic type would show slight colour.

The Eyepiece

This is made of two plano-convex lenses of the same material separated by a calculated distance, and is known as a Huyghen's eyepiece (Fig. III. 6). The focal length of the field lens which receives the

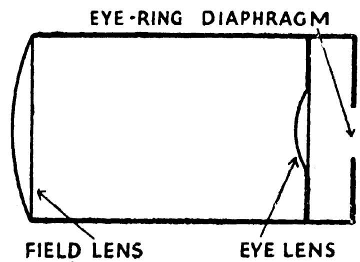

Fig. III. 6. Microscope objective.

light from the objective is three times that of the eye lens. The combination behaves essentially as a simple microscope. They are made with magnifying powers of ×6 to ×16, and the magnifying power of the eyepiece used should be chosen with due regard to the numerical aperture and magnification of the objective. When properly designed, the light emerging from the eyepiece is concentrated into a circle of light (the eye-ring) of about the same size as the pupil of the eye (3 mm.), which is automatically placed in this position by the correct positioning of a diaphragm behind the eyelens. This gives the best visibility.

The Condenser

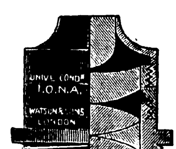

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Fig. III. 7. Microscope condenser.

The normal type (Fig. III. 7) consists of a corrected lens combination which concentrates the white light from the illuminant on to the small object, which must be semi-transparent, such as the very thin sections used in biological work. These sections are mounted on a microscope slide, and placed on to the sub-stage. The varying degrees of absorption and refraction of the light through the section show up the detail against a white background.

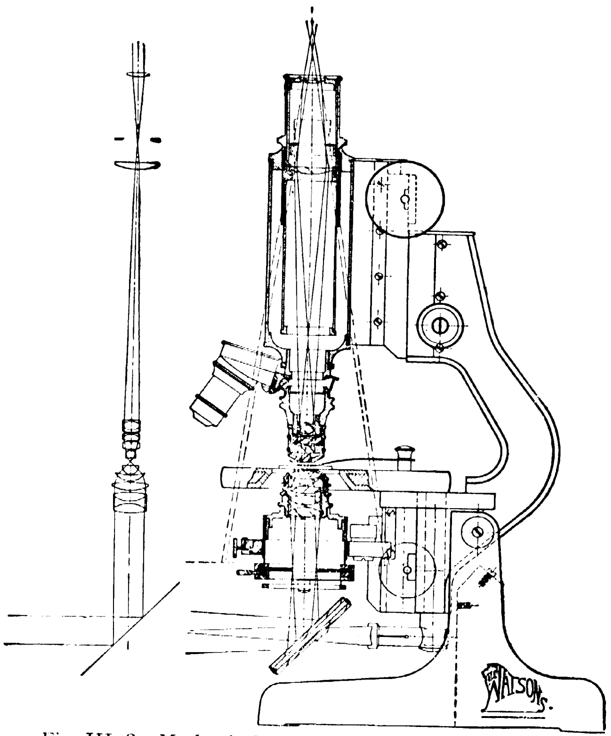


Fig. III. 8. Mechanical and optical system of a microscope.

In *Dark Ground Illumination* the light is so directed on to the slide that none of the direct light from the condenser can enter the objective. The image is formed by the light which is differentially refracted and scattered by the object, and so can enter the microscope. As a result the detail is shown up brilliantly against a dark background.

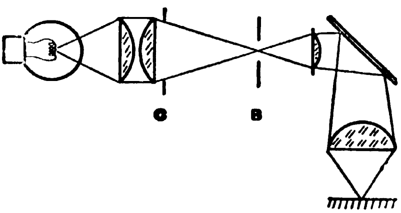


Fig. III. 9. Vertical illuminator.

When opaque objects, such as a polished surface of a metal, have to be examined, a *Vertical Illuminator* (Fig. III. 9) is used. This attachment enables light entering from the side to be thrown down through the objective on to the surface, either by a prism, or by a piece of plane glass. The light which is differentially reflected and scattered from the specimen is collected by the objective. Using the prism the light thrown down is more intense than with the glass plate, but as only part of the aperture

of the objective can be used for collecting the light, there is a reduction in the resolving power, a defect from which the glass plate does not suffer. A microscope in which the vertical illuminator is built in is called a *Metallurgical Microscope.*

Petrological or Mineralogical Microscope

This is designed for the examination and recognition of crystals, including such as occur naturally in rocks. It is thus of particular value in crystallography and geology. The specimen is worked to a very thin, highly polished, plane, semi-transparent section, fixed to a microscope slide, and examined by transmitted light in the standard way. Between the mirror and the specimen a polarising device, usually a Nicol Prism, is placed, which allows light vibrating in only one direction to pass. This plane polarised light is modified on passing through the crystal, and is collected in the usual way by the objective. In front of the eyepiece a second similar device is fixed and orientated in such a way that without the crystal the field of view is dark. With the crystal in position (which can be rotated on the special divided sub-stage) a characteristic coloured pattern is observed which gives information of its crystal structure.

Binocular Microscope

Vision with both eyes gives a stereoscopic effect because of the slightly different images produced in each eye. It enables depth to be judged. (The reader should try threading a needle with one eye closed.) Such a stereoscopic view of the magnified image of the object is produced by using a "double microscope," one for each eye, inclined at slightly different angles. For high powers the two microscopes have a common objective.

Depth of Focus

As the numerical aperture of the objective increases, the depth of view which remains in sharp focus decreases considerably. For example with a 25 mm. objective of *N.A.* about 0.1 which gives a limit of resolution of 2.5×10^{-4} cm. (magnification about 80), the depth of focus is 2.5×10^{-3} cm., that is ten times the resolving limit, whereas with a 2 mm. oil immersion of *N.A.* 1.5 and resolving limit 2×10^{-5} cm. (magnification 1000), the depth of focus is only 6×10^{-6} cm. (1/10 wavelength), only about one-third the resolving power limit. Anything lying outside this depth will give a blurred image. This means that, especially for high powers, an extremely fine movement of the microscope tube relative to the substage is essential in order to focus accurately. This is provided by the fine adjustment, an essential mechanical feature of a good microscope.

General

The study of the minute, both animate and inanimate, was only made possible by the invention and development of the compound microscope, and it has proved of the greatest value in innumerable fields, particularly in those of biology, medicine and metallurgy.

The detailed structure of the living cell was for the first time seen under the microscope, and living bacteria and microbes of all kinds can be seen and studied.

The Ultra-Violet Microscope

The limit of numerical aperture is reached in the modern microscope, so that the only method by which the resolving power can be improved is by a reduction in the wavelength of the light used, since for the same *N.A.* the least distance "R" of the object which can be made visible is directly proportional to the wavelength. This is achieved in the *Ultra-Violet Microscope* in which the U.V. light of wavelength about 3×10^{-5} cm. is used. It follows that the useful limit of magnification is now doubled, at about 2,000. Since the eye is not sensitive to this wavelength, a projection lens is used instead of the eyepiece, and the final image photographed. The optical components are made of quartz only, since glass is opaque to the U.V. The component lenses, however, are simpler in design, for a single wavelength from a mercury arc is used, so that no "colour" correction is necessary.

This U.V. microscope has proved of great value since it clearly shows fine structure which the visual light microscope cannot resolve.

THE ELECTRON MICROSCOPE

It might appear from what has been said that it is only necessary to reduce the wavelength to increase the magnifying power to any desired extent. For example, if X-rays of wavelength between 10^{-8} cm. and 10^{-10} cm. could be used, the linear magnifying power of the microscope would be millions of times. In fact, however, this cannot be done, because of the atomic or granular structure of matter. In order that regular surface reflection and refraction should take place, the wavelength used must be hundreds of times greater than the distance between the atoms. Now the distance between the atoms of a solid is rather more than 10^{-8} cm., so that X-rays cannot be reflected or refracted at the surface. Most of the X-rays pass between the atoms, and those that meet an atom are scattered in all directions. This means that it is impossible to produce lenses for X-rays, so that no focusing effect with X-rays is possible. Consequently an X-ray microscope is an impossibility.

For a long time it appeared as if the limit of magnification had been reached with the U.V. microscope, and that the last word had been said in microscopy.

In 1925 the subject of *wave mechanics* was opened by some brilliant theoretical deductions of Louis de Broglie. This was followed soon after by further most important theoretical work by Schrödinger and Heisenberg. Among other things they showed that moving electrons were associated with a wave whose wavelength could be calculated from the formulæ $\lambda = h/mv$, where h is an important physical constant called Planck's constant, m the mass of the electron in grams, v the velocity of the electron in cm/sec., and λ the wavelength in centimetres.

By 1928, ample experimental evidence had verified this remarkable prediction, and had shown that these waves had many of the attributes of X-rays so far as their behaviour with matter was concerned. In addition the electron is the ultimate unit of electric charge, so that it can be accelerated by applying suitable electric fields and so given any desired velocity within very closely controlled limits, and thus any

desired wavelength. For example an accelerating voltage of 60,000 produces a wavelength of about 6×10^{-10} cm. equivalent to short X-rays about one hundred-thousandth part of the wavelength of light.

In 1926 Busch had shown that by arranging suitably short magnetic or electric fields through which the electrons passed axially, a diverging pencil of electrons could be focused or converged to another point. This is identical with the behaviour of light which, diverging from a point of the object may be caused to converge to an image point by passage through a convex lens. For this reason these specially-designed electric or magnetic fields are known as electrostatic and magnetic electron lenses respectively.

The combination of electron waves and electron lenses provides the essential ingredients from which the electron microscope has been built.

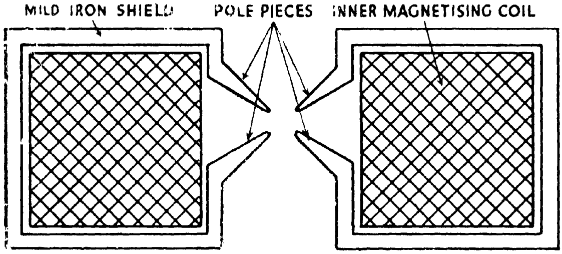


Fig. III. 10. Magnetic electron lens.

Electron Lenses

Fig. III. 10 shows the construction of a magnetic electron lens in section. The magnetising coil is surrounded by a shield of mild steel ending in specially-shaped pole pieces, producing a very short concentrated magnetic field. The electrons passing through this field are so deviated that a divergent pencil which enters the lens leaves as a convergent one. The minimum focal length at present attainable with this type is about 4 mm., the focal length being adjusted by varying the magnetising current. Fig. III. 11 illustrates the construction of an electrostatic electron lens. The outer specially-shaped diaphragms are earthed, and the centre one, which is fixed to an insulator, is connected to the source of high potential. The three apertures have a diameter of about 1 mm. and are about 2 mm. apart. The diaphragms are made from highly-polished chromium-nickel steel, and all parts are carefully rounded to minimize the danger of sparking. It is shielded from external magnetic fields by a double magnetic shield, the outer one being of soft iron, the inner of Mu-metal. The focal length

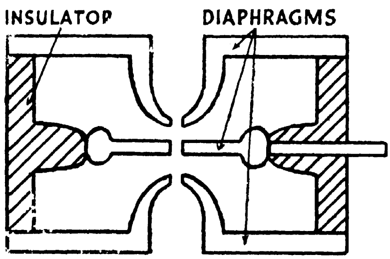


Fig. III. 11. Electrostatic electron lens.

may be as small as $2\frac{1}{2}$ mm. For a number of technical reasons, the magnetic lens has proved more advantageous, so that the majority of electron microscopes use this type of electron lens.

Limit of Magnification

This can be calculated by the same formula as for the ordinary microscope, namely $0.02/R$, where $R = \frac{1}{2}\lambda/NA$.. as before. The standard accelerating voltage used is 60,000 for which the equivalent $\lambda = 6 \times 10^{-10}$ cm. The numerical aperture so far possible is only about 0.001, but even with this small value, the useful magnification possible is about 70,000, which is a very great improvement even on the U.V. microscope. Some idea of what this means may be gained from the fact that at this magnification an individual bacterium would appear to be the size of a football, and a drop of water the size of a swimming bath.

Lens System

In order to produce these enormous magnifications with a reasonable size of microscope two stages are used. Fig. III. 12 illustrates how the final image is produced. Bundles of electron rays leaving the source are accelerated and then focused on to the minute object by the electron condenser lens. The parts of the object of greater mass thickness scatter the electrons more than other parts. This means that less electrons (or perhaps none) pass through these parts, whilst the other parts are more transparent to the passage of the electrons, so that most of them pass through without appreciable change of direction or velocity. The electron pencils diverging from each point of the object are converged by the objective producing the intermediate image. A fluorescent screen can be temporarily introduced to ensure correct focusing. Most of the forward scattered electrons are intercepted by the stop, since otherwise they would produce fogging of the back-

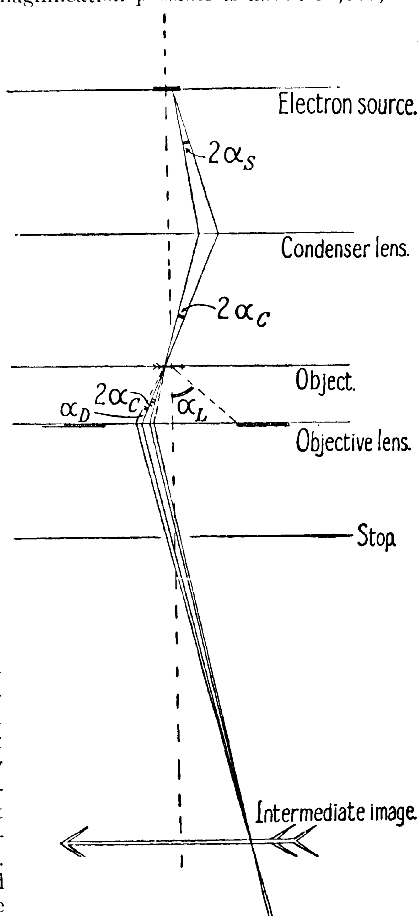


Fig. III. 12. Image formation by electron microscope.

ground. A projection lens behind the intermediate image produces the final image. This also may be examined and sharply focused by the aid of a second temporary fluorescent screen, this screen being then replaced by a photographic plate.

In order to realize the magnifications possible, the length of the microscope proper would be over twelve feet. It is reduced to about three feet by reducing the overall magnification to a maximum of 20,000. A photographic plate of sufficiently fine grain is used and further magnification is produced by enlargement up to the extent justified by the detail which exists in a compressed form on the negative.

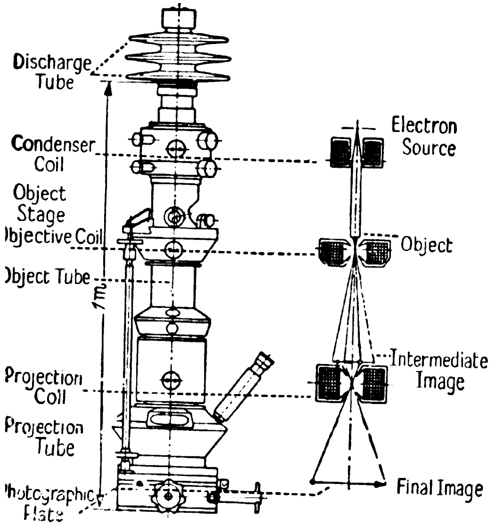


Fig. III. 13a. Details of early commercial electron microscope.

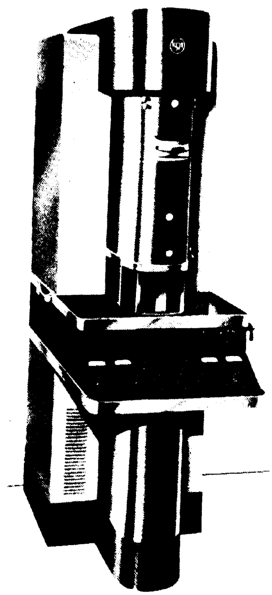


Fig. III. 13b. View of latest, all-enclosed model of R.C.A. electron microscope.

Fig. III. 14 shows two photographs of the etched surface of a specimen of stainless steel, both with a magnification of about 5,000. The first was taken with a metallographic light microscope, the other with the electron microscope. The striking improvement in the detail and structure of the crystal faces illustrates the large gain in resolving power. The magnification of the light microscope photograph is well beyond that justified by its resolving power, whilst that of the electron microscope can be considerably increased to bring out the full detail.

Vacuum Control

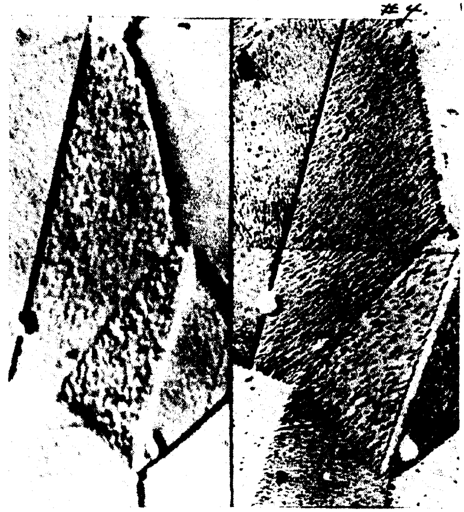


Fig. III.14. *Left.* Etched surface of stainless steel taken with a light microscope (5,000 magnification). *Right.* Same surface taken with the electron microscope. Same magnification (Polystyrene-silica replica method).

As in most electronic devices, the space in which the electrons move must be highly evacuated, otherwise they will be scattered in all directions by collision with the molecules of gas. To this end, the electron source, accelerating electrode, condenser lens, objective lens, projection lens, specimen and photographic plate are all enclosed in a single tube which can be continuously evacuated by suitable high-speed vacuum pumps. (The tube can be evacuated to the maximum permissible working pressure in about two minutes.) One important consequence of this is that biological specimens, which contain much water, tend to be dehydrated, so that the structure may be altered. Again if very minute bacteria and viruses are being examined, there is a limit to the electron current and exposure time which may be used, otherwise these minute organisms will be destroyed. This is one of the advantages of using relatively small initial magnifications.

Stereoscopic Electron Microscope

Because of its very low *N.A.* (0.001), the depth of focus is very great even with the highest magnifications so far used (about 200,000). To produce the stereoscopic effect, a special object carrier is introduced into the microscope which can be tilted by a few degrees between two successive exposures. The two corresponding photographs are then examined under a stereoscope and produce a vivid impression of depth and solidity.

Uses of the Electron Microscope

The first commercial model was made in 1940, but already these microscopes are in use in many fields of science and industry. At first they were used primarily as instruments of research, but have now also been adopted for production control in processing plants, and for analysis and control in the bacteriological field.

In the chemical field they are being used in determinations of particle size and shape, analysis of materials, detection of impurities and study

of molecular structure. In the metallurgical field they are used in the analysis of ores, studies of processing and examination of fine surface details such as pearlitic formations and in the bacteriological field for viewing and photographing bacteria and viruses too small to be seen with the light microscope, and for studying bacterial structure, flagella and other details never before visible. In the fields of botany, zoology, anatomy and histology, fine structure of living matter previously invisible can now be studied in detail, and finally in the medical field the effects of drugs, such as penicillin, on harmful bacteria can be studied, and much more detailed information of diseased tissue can now be obtained.

The field of use of the instrument is continually being widened, and there seems no doubt that the electron microscope will contribute in no small measure to important progress in almost every field of human endeavour.

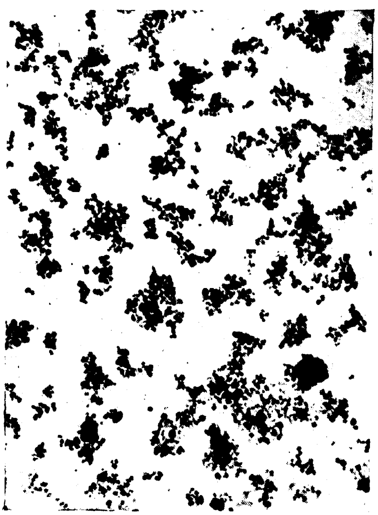


Fig. III. 15. Minute particles of colloidal titanium dioxide, an extremely fine pigment. The tiny particles are only one five-millionth of an inch in diameter. Magnification 100,000 times.

Fig. III 16. Electron microscope photograph of unstained untreated bacteria (magnification 55,000 times), showing the extreme length of the flagella as well as the connecting cell wall and internal protoplasm.

CHAPTER IV

POLARIMETERS

A polarimeter is an instrument used for detecting and measuring the quantity of any substance which possesses the particular property known as optical activity. Thus we find the polarimeter is used in industries dealing with the production of sugar, starch, jam, condensed milk, wine, essential oils, drugs, etc. In each case an optically active substance is estimated quantitatively by the polarimeter. The medical profession also makes use of the polarimeter for the estimation of sugar in urine.

To understand how a polarimeter works, one must have some knowledge of the properties of plane-polarised light. Light is a wave motion, the plane of vibration being perpendicular to the direction of propagation (Fig. IV. 1). The intensity of light is proportional to the square of the amplitude (Fig. IV. 1). In ordinary light the vibrations occur in every

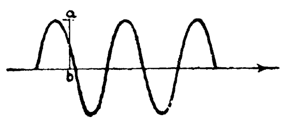


Fig. IV. 1. ab. is the amplitude of vibration.

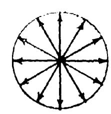


Fig. IV. 2. Light approaching observer.

Fig. IV. 3. Plane-polarised light.

possible plane about the direction of propagation as axis (Fig. IV. 2). In plane-polarised light the vibrations are limited to one plane (Fig. IV. 3). The most useful method for producing plane-polarised light is by the double refraction of Iceland spar (calcite) which can readily be obtained as rhombs (solid with six faces each one being a parallelogram, the angles of which are 102° and 78°). When such a crystal is placed over a black dot on paper, two images will be seen by an observer (Fig. IV. 4). This phenomenon is known as double refraction and is always observed in any direction except one—the *optic axis*. At corners A and H all the angles are obtuse. A line through A (or H) making equal angles with the three faces meeting at A, and any line parallel to it, is the optic axis of the crystal. If P is viewed through the crystal along direction AX, only one image will be seen.

A plane through the optic axis and perpendicular to a pair of opposite faces is called a principal section.

It has been shown that ray PO (the ordinary ray) and ray PE (the extraordinary ray) are both plane-polarised. Further-

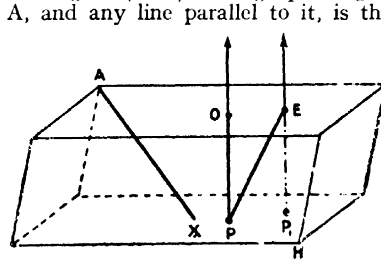


Fig. IV. 4. P is a black dot on paper. P_1 is the second image. AX is the optic axis.

more, if the incident light is normal to a surface of the crystal the vibrations of the ordinary ray are perpendicular to the principal section whereas those of the extraordinary ray are parallel to the principal section.

The Nicol prism is a means of preparing polarised light by using the extraordinary ray only. A calcite crystal is taken such that ABGF is

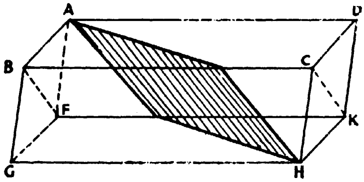


Fig. IV. 5. Shaded portion is plane of cut parallel to diagonal BF.

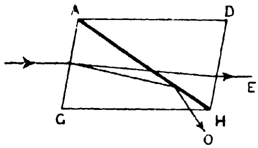


Fig. IV. 6. ADHG is section of crystal. AH is film of Canada balsam. O is the ordinary ray and E the extraordinary ray.

a rhombus and AD about three times the length of AB (Fig. IV. 5), and is cut through the blunt corners A and H by a plane parallel to diagonal BF. The cut faces are polished and cemented together by a film of Canada balsam. Canada balsam is used since if the angle of incidence on face ABGF is not too great, the ordinary ray will be totally reflected to the side whereas the extraordinary ray will pass through (Fig. IV. 6). The sides of the prism are blackened to absorb the ordinary ray.

The simple Nicol prism has certain defects and these have been overcome by various modifications. The prisms used in modern polarimeters are the Lippich (Fig. IV. 7) and Glan-Thomson (Fig. IV. 8). Both are right prisms with square ends.

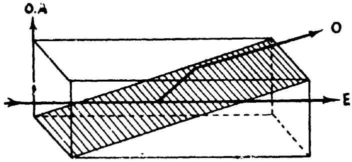


Fig. IV. 7.

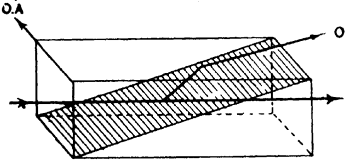


Fig. IV. 8.

OA is the optic axis. The shaded portion is the section of cut. O and E are the ordinary and extraordinary rays respectively.

To study the properties of plane-polarised light a second Nicol is necessary and this is called the analyser. Suppose two Nicols are placed with their corresponding principal sections parallel (Fig. IV. 9). Then the light which is polarised by the polariser will pass through the analyser

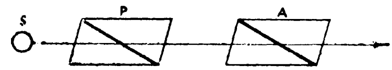


Fig. IV. 9. S is a light source. P is the polariser. A is the analyser.

with undiminished intensity. If the analyser is rotated about its horizontal axis, the intensity of the light transmitted will vary according to the value of θ (Fig. IV. 10). Only the value Oa (Op cos θ) gets through, and as θ gets bigger, Oa gets smaller, and when $\theta = 90°$, Oa is zero, i.e., no light is transmitted and the field is black. In this condition the Nicols are said to be crossed. Increasing θ beyond 90° will again allow light to pass through and when $\theta = 180°$ the field will have maximum intensity again. When $\theta = 270°$ the Nicols are crossed and with $\theta = 360°$ the analyser is back in its original position.

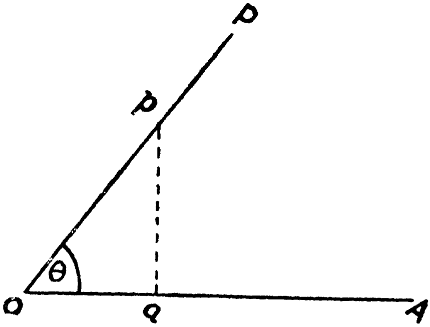


Fig. IV. 10. OP and OA are parallel to the principal sections of the polariser and analyser respectively when angle of rotation is θ. Op and Oa are the amplitudes of vibration in OP and OA respectively. (Oa is the projection of Op on OA.)

When certain substances are interposed between crossed Nicols, the field is no longer black. To get blackness again the analyser must be rotated through some angle. Therefore the plane of polarisation has been rotated by the substance and substances which can do this are said to be *optically active*. If the analyser has to be rotated to the right (clockwise relative to an observer receiving the light) to restore the black field, the substance is said to be dextrorotatory (+); if to the left (anti-clockwise) then lævorotatory (—). To restore the black field the analyser could be rotated through say 30° to the right or 150° to the left. In practice the smaller angle is always used.

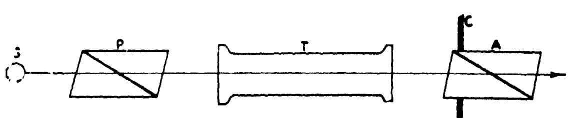


Fig. IV. 11. S is a source of monochromatic light (i.e., light of one wave-length). P is the polariser. A is the analyser mounted at the centre of a rotating circle C fitted with a scale from which rotation can be obtained. T is a tube of definite length fitted with plane glass covers and contains the solution of the optically active substance.

An instrument that measures the rotation of an optically active substance is called a *polarimeter*. The essential feature of any polarimeter is a combination of two Nicols: the polariser and analyser. The simplest polarimeter would have the following arrangement (Fig. IV. 11).

Such an instrument would not be very accurate since it is difficult to determine the exact point of minimum intensity, a value of

$\pm 2 - 3°$ about the actual zero giving the same minimum intensity. This difficulty is due to the fact that the human eye cannot judge absolute intensities accurately. It can, however, compare intensities accurately, and so in all polarimeters the field is divided into two or more parts which can be matched with an accuracy of $\pm 0.01°$.

Many end point devices have been invented but only two are used in modern polarimeters, the Laurent and Lippich devices. A polarimeter which has its field divided into two parts is called a half-shadow instrument.

The Laurent Half-Shadow Polarimeter

(Fig. IV. 12 shows one possible arrangement.)

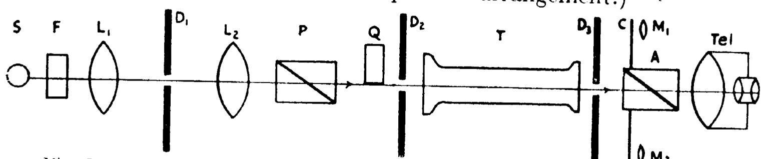


Fig. IV. 12. S is a source of monochromatic light. F is a filter. L_1, L_2, M_1 and M_2 are lenses. D_1, D_2 and D_3 are diaphragms. P is the polariser (Lippich or Glan-Thomson type). A is the analyser (Glan-Thomson type). Q is a quartz half wave plate. T contains the optically active substance. C is a rotating circle with a scale. Tel is a focusing telescope.

Operation

A source of almost monochromatic light is made quite monochromatic by being passed through a filter. The first lens focuses the image of the light source on the first diaphragm which is placed at the focus of the second lens so that a beam of parallel light passes through the rest of the instrument. The three diaphragms limit the diameter of the beam and at the same time give rise to a circular field. Half of the beam of polarised light passes through the quartz plate. Then the whole beam passes through the substance under investigation and reaches the analyser which is mounted at the centre of a rotating circle fitted with a clamp and slow motion, and its rotation can be read by two opposite verniers to $\pm 0.01°$. Magnifying lenses are fitted over each vernier. Finally the beam of light is received by the observer via a telescope which is focused on the vertical edge of the quartz plate.

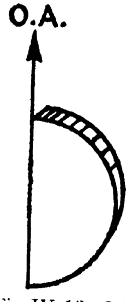


Fig. IV. 13. OA is the optic axis.

Function of the quartz half-wave plate

The quartz half-wave plate is a semicircle cut with its faces parallel to the optic axis (Fig. IV. 13). This is mounted so that it covers half the field (Fig. IV. 12). Quartz cut as above is optically active and its rotation depends on (a) its thickness; (b) the angle between its optic axis and the vibration plane of the incident polarised light; (c) wavelength of the light. By using monochromatic light and making the thickness of the quartz plate equal to an odd number of half-wavelengths (hence name, half-wave plate), the rotation is 2θ (Fig. IV. 14a). Thus the beam of light which reaches the analyser consists of two halves, one half with its vibration plane along OP (the half which did not pass through the quartz plate), and

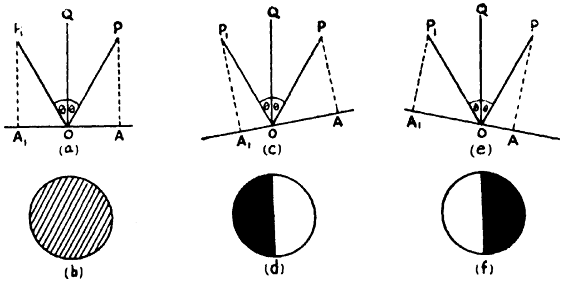


Fig. IV. 14. OQ is the optic axis of the quartz plate. OP is the amplitude and vibration plane of the light incident on the quartz plate. OP_1 is the amplitude and vibration plane of the light emerging from the quartz plate. $\angle POQ = \angle P_1OQ = \theta$. AOA_1 is the vibration plane (principal section) of the analyser. OA and OA_1 are the component amplitudes of vibration of OP and OP_1 respectively in AOA_1.

the other half with its vibration plane along OP_1 (the half which passed through the quartz plate). The intensity of each half of the field will now depend on the angle between the vibration plane of the light and the principal section of the analyser. In Fig. IV. 14a the principal section of the analyser is midway between the two vibration planes and so the two halves of the field have equal intensity (Fig. IV. 14b). This position is taken as the end point. Movement of the analyser from this position in either direction causes one or other half of the field to become dark (Fig. IV. 14c, d, e and f).

$\angle$ POP_1 is called the half-shadow angle and the smaller it is the less the analyser need be rotated to get half the field black, i.e., the greater is the sensitivity. On the other hand, the smaller the angle the less the light that illuminates the field, i.e., the smaller is AOA_1. By having an arrangement whereby the polariser can be rotated with respect to the quartz plate the value of the half-shadow angle can be made any value desired and so the instrument will have an adjustable sensitivity. The actual value chosen depends on the transparency of the solution under investigation. The less transparent the solution the greater the illumination necessary and so the greater must be the half-shadow angle, with corresponding decrease in sensitivity.

The Laurent polarimeter has the advantage of adjustable sensitivity. Its disadvantage is that it must be used with monochromatic light. In practice the quartz half-wave plate is cut for the sodium D line.

The Lippich Half-Shadow Polarimeter

The Lippich optical arrangement replaces the quartz half-wave plate of the Laurent device by a small Lippich prism which covers half the

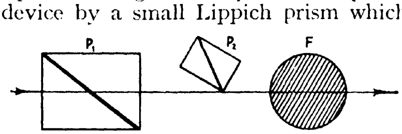


Fig. IV. 15. P_1 is the Lippich polariser. P_2 is the small Lippich polariser. F is the field at the end point.

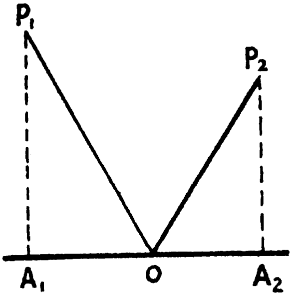


Fig. IV. 16. OP_1 is the amplitude and vibration plane (principal section) of the light from P_1. OP_2 is the amplitude and vibration plane (principal section) of the light from P_2. A_1OA_2 is the vibration plane (principal section) of the analyser. OA_1 and OA_2 are the component amplitudes of vibration of OP_1 and OP_2 respectively in A_1OA_2.

field and has its principal section making a small angle with the principal section of the polariser (Fig. IV. 15).

From Fig. IV. 16 it can be seen that of the light from P_1 that reaches P_2, only the component in the principal section of P_2 passes through, i.e., the plane of polarisation of half the beam is rotated through $\angle P_1OP_2$. Thus the fields of view obtained will be as for the Laurent device (Fig. IV. 14a, b, c, d, e and f). The telescope is focused on the inner edge of P_2.

The advantages of the Lippich end point device are (a) adjustable sensitivity, i.e., half-shadow angle can be varied, (b) can be used for white light or any monochromatic light.

The Lippich end point device is said to be the most accurate, and the sensitivity can be increased by using a Lippich triple shadow device (Fig. IV. 17).

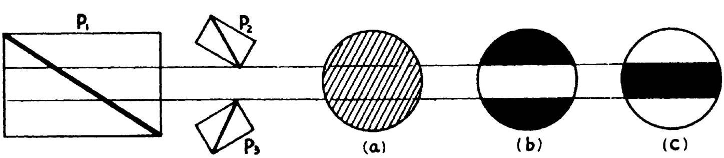


Fig. IV. 17. P_1 is the Lippich polariser. P_2 and P_3 are the small Lippich polarisers. A is the field at the end point, b and c are the fields when the analyser is crossed with the outer and inner fields respectively.

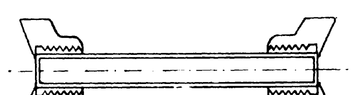


Fig. IV. 18

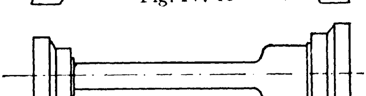


Fig. IV. 19

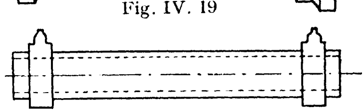


Fig. IV. 20.

Polarimeter Accessories

Light Sources. Various wavelengths are used but the most common is the sodium D line (5893 Angstroms or 5893×10^{-8} cm.). This is a bright yellow line. Several firms are now making excellent electric sodium vapour lamps which give very high illumination. For accurate work this light must be filtered, since it is not absolutely monochromatic. A cell 1 cm. thick and containing a 9% solution of potassium dichromate is satisfac-

tory. Glass filters of equivalent absorbing power are now being made and these are more convenient to use.

Tubes. These are of various types, but whatever the type the following requirements must be satisfied.

(1) the diameter must be large enough to take the whole of the incoming light,
(2) the cover glasses must be parallel, perpendicular to the length of the tube and free from strain,
(3) the length of the tube must be accurate,
(4) the tube must be evenly centred in the trough of the polarimeter.

The tube may be made of glass, fused silica or metal. Common lengths are 25, 50, 100, 200, 220 and 400 mm. The simplest tube is a glass tube of uniform bore. Metal collars, threaded to fit the screw caps, are cemented on (Fig. IV. 18). Enlargement of one end gives the opportunity of removing any air bubble from the field of view (Fig. IV. 19). For work at definite temperatures, metal jackets are used (Fig. IV. 20).

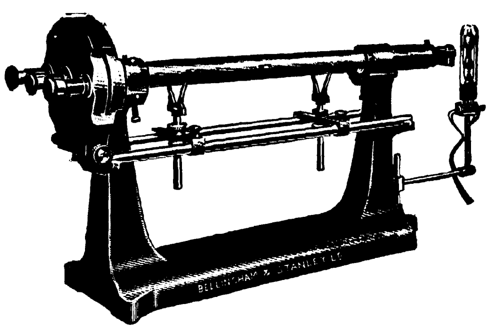


Fig. IV. 21

Fig. IV. 21 shows a polarimeter made by Bellingham & Stanley Ltd It is fitted with a glass circle which is illuminated by transmitted light The polariser is special to this firm. Two *long* calcite rhombs are placed together at a small angle. Due to the unusual length, the ordinary ray is refracted to the side when it is absorbed (Fig. IV. 22). Since the principal sections of the two rhombs are not parallel, the two beams will have their vibration planes inclined to one another at a small angle which will be the half-shadow angle.

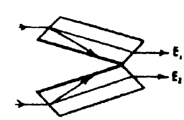


Fig. IV. 22. E_1 and E_2 are the extra-ordinary rays.

Specific Rotation

The rotation of a given substance depends on (a) concentration, (b) temperature, (c) length traversed by the light, (d) wavelength of the light. To compare rotations of different substances a quantity called the *specific rotation* is used and is denoted by $[\alpha]_\lambda^t$ where t is the temperature (usually 20° C.) and λ is the wavelength of the light used (usually the

sodium D line). The value of the specific rotation is given by (a) for pure liquids :

$$[\alpha]_D^{20^\circ} = \frac{\alpha_D^{20^\circ}}{l\,d}$$

: (b) for solutions in an optically inactive solvent :

$$[\alpha]_D^{20^\circ} = \frac{\alpha_D^{20^\circ}}{l\,c}$$

where $\alpha_D^{20^\circ}$ is the observed rotation, l is the length in *decimetres*, d is density in gm. per ml. and c is the number of gm. of solute per ml. of solution.

Saccharimeters

Since the rotation is proportional to the concentration, sugar is bought and duty is paid on the amount of rotation of the specimen.

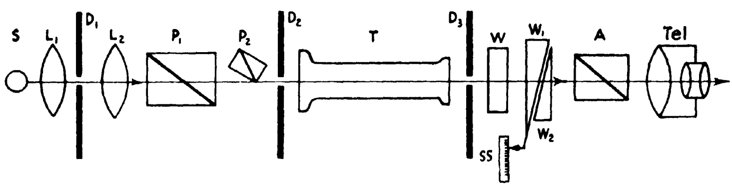


Fig. IV. 23. S is a source of white light, L_1 and L_2 are lenses. D_1, D_2 and D_3 are diaphragms. P_1 and P_2 are the Lippich polarisers. T contains the sugar solution. A is the analyser (Glan-Thomson type). Tel is the focusing telescope. W is a dextrorotatory quartz plate. W_1 and W_2 are laevo-rotatory quartz wedges, W_1 being movable by a rack-motion, and W_2 is fixed. S.S. is the sugar scale fitted with a vernier.

A polarimeter designed entirely for sugar estimation is called a saccharimeter. Raw sugar solutions are highly coloured and so a powerful source of light is needed to illuminate the field. Before the advent of the electric sodium vapour lamp, the only source powerful enough was white light which necessitated the use of a quartz wedge as compensator. Fig. IV. 23 shows the optical arrangement of a *single-wedge* saccharimeter.

Apart from W, W_1, W_2 and S.S., the other parts operate as in the Lippich polarimeter.

Function of W, W_1, W_2 and S.S.

Unequal rotation of light of different wavelengths by an optically active substance is called *rotary dispersion.* Lævo-rotatory quartz has about an equal and opposite rotary dispersion to a sugar solution so that the unequal rotations of the different wavelengths in white light by the sugar solution are neutralised by the quartz.

The polariser and analyser are stationary, being fixed to give equal half fields in the absence of W, W_1 and W_2. These are inserted and when the thickness of W_1 and W_2 together is equal to W the light passes through without rotation. The sugar solution is now interposed and

W_1 is moved until equal half fields are again obtained. S.S. is a scale from which the sugar concentration can be obtained.

There are several scales in use in saccharimetry and an attempt is being made to make the International Sugar Scale (I.S.S.) universal. This scale makes the rotation of 26 gm. of pure sucrose in 100 ml. of water at 20° in a 200 mm. tube equal to 100 divisions. Thus (for example) a rotation of 25 divisions would be equal to a concentration of 6.5 gm. of sucrose in 100 ml. of water.

Due to the difficulty in cutting these quartz wedges accurately and due to the production of electric sodium vapour lamps of high intensity, there is a tendency to avoid the use of quartz wedge saccharimeters; e.g., Bellingham & Stanley Ltd. have made a saccharimeter using the direct reading sugar scale on a polarimeter (Fig. IV. 24).

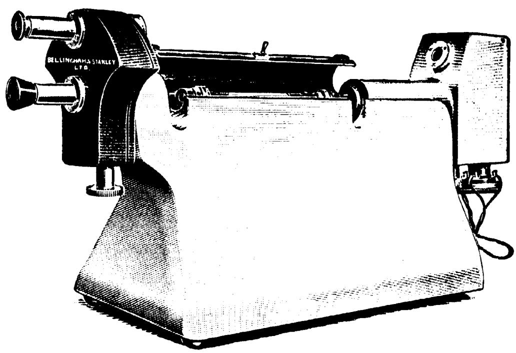


Fig. IV. 24.

CHAPTER V

PHOTOMETERS

The Grease-spot Photometer

It is convenient to begin with a description of a very simple photometer. From a consideration of its working will appear the basic principles of all photometers and a consideration of its limitations and defects will make apparent the need for the refinements met with in more elaborate instruments.

If a spot of oil or grease is dropped on to a piece of white paper which is held between an observer and the light, the spot appears brighter than the clean paper around it, while if the observer is between the paper and the light, the spot appears darker. The spot on the paper resembles the window of a room which appears to an observer in the room bright compared to the wall in the daytime with the light outside, and darker than the wall at night time with the room illuminated. This is so because the window lets through nearly all the light which falls on it while the wall reflects back a considerable portion of what falls on it. In the case of the grease spot on the paper the spot lets through a greater proportion of the light falling on it, while the clean paper reflects back a greater proportion. If the paper is equally illuminated on each side, the spot will appear neither brighter nor darker, and, in fact, by turning the paper at various angles to the light in a room, the spot may be observed nearly to disappear for a certain orientation.

Fig. V. 1 shows a simple arrangement for comparing two light sources by this method. The distances from the grease spot of candle and of lamp are adjusted until the spot disappears as nearly as possible, which occurs when equal illumination on each side has been secured. The relative powers of the candle and lamp are then inferred from the distances c and l. Obviously if l exceeds c, the lamp is more powerful than the candle. It may be found by experiment that, if after a balance is obtained, a second candle is placed very close to the first but not shielding it from the grease spot, the distance l needs to be reduced to $.71\ l = l/\sqrt{2}$, to regain a balance of illumination. This means that a lamp produces on a screen an illumination which is inversely proportional to the square of its distance from the screen. The same result may be inferred theoretically, for if two similar shaped screens are placed opposite a lamp so that the further

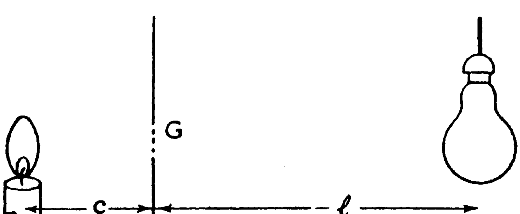


Fig. V. 1. Grease-spot photometer.

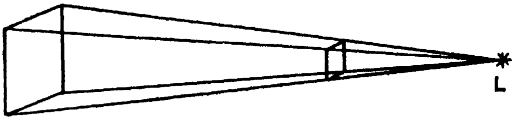


Fig. V. 2. Demonstration of inverse square law.

one coincides with the shadow of the nearer one exactly (Fig. V. 2), the further screen would receive, in the absence of the nearer one, the same amount of light as is received by the nearer screen. Thus the intensities of illumination (light per unit area) are inversely proportional to the areas of the screens, and the areas are proportional to the squares of their distances. Wherefore, in Fig. V. 1 we have

Power of lamp : power of candle : : $l^2 : c^2$

The grease-spot photometer, like all photometers, merely compares the power of two sources, so that the absolute power of any source can be obtained only by comparing it with some standard source whose value is defined as so many candle-power. Furthermore, the grease-spot photometer measures the illuminating power of the source in a particular direction (horizontal in the case of Fig. V. 1). Most photometers resemble the grease-spot photometer in this respect; those which measure the total light emitted in all directions by a source, are called integrating photometers. It is evident that if either of the light sources were variable in intensity, we could secure a balance without varying the distance c or l. This method, employing a variable standard source, is more common than the fixed source and variable distance method.

The grease-spot photometer suffers from two defects. The first arises from the fact that the relative brightness of spot and paper depends upon the angle at which they are viewed, because the clean paper diffuses widely the light which it reflects, while the grease spot diffuses relatively little of the light which it allows to pass through. The defect may be overcome by arranging that each side is viewed at the same angle; all photometers of the grease spot principle incorporate a viewing tube or eyepiece to secure this condition. The second defect is noticed when sources of different colours are being compared. If, for instance, one source is ruddier in hue than the other, the effect in a pronounced case is that one can obtain a pink spot on a bluish background on one side, and a bluish spot on a pink background on the other side. Different observers will disagree, in general, in their judgments of equal intensity of these colours, depending upon their subjective reactions to the colours. The assessment of equal intensity is difficult in the same way as would be the assessment of the relative intensities of two odours, one of roast pork, and the other of spirits, if the two judges were, one a vegetarian and the other a teetotaller. This is a very real difficulty in all photometric work, although some instruments partially avoid it. The opinion of practised photometrists is that long experience of photometry tends to make all observers react similarly to various hues. If this is so, it has the advantage of securing uniformity of the estimation of the powers of lamps, if made by experienced photometrists, but it does not follow that the estimate is an accurate one for assessing the values of lamps to the man in the street, whose subjective reactions to colour have not been conditioned in the same way.

Standard Sources

The historic British Standard is the British Standard candle, made to specified shape and size of spermaceti wax. Owing to the difficulty of controlling the wick by specification it was an unsatisfactory standard, and is not now used. Its memory is preserved in the name of the unit of power, the candle-power. A standard of German origin, used in this country and widely on the Continent, is the Hefner lamp which burns amyl acetate, and is provided with an arrangement to trim the wick to a predetermined height. The Hefner lamp is defined as being of 0.9 candle-power in a horizontal direction. The Vernon Harcourt pentane lamp is largely used as a standard in America. This lamp is provided with a carburettor in which pentane vapour is mixed with pre-heated air and fed to the flame under closely controlled conditions. It is defined as being of 10 candle-power in a horizontal direction, which makes the Hefner, the Vernon-Harcourt, and the old British candle-power, nearly equal to each other.

Few industrial establishments making photometric measurements employ any of these primary standards as it is more convenient to use an electric lamp as a secondary standard. In this kingdom an electric lamp can be calibrated against a primary standard at the National Physical Laboratory. It may then be used in a photometer to calibrate another electric lamp as a variable tertiary standard, i.e., to determine the candle-power of the tertiary standard for various voltages across its terminals. Provided the filament temperature is kept well below the normal operating temperature of the lamp, such a standard will preserve its characteristics for many hours, providing many hundreds of measurements. Control by voltage is preferable to control by current, since the candle-power of an electric lamp varies more slowly with voltage change than with current change.

Essentially the same as a variable standard is a fixed standard with a means for intercepting some of its light. The interceptor may be a shutter provided with apertures of variable size, and revolving so fast that the flicker is imperceptible to the eye. Or it may be a wedge of neutral tinted glass calibrated so that the fraction of the light transmitted may be known from the thickness of the part of the wedge in its path. A favourite interceptor is a pair of crossed Nicol prisms; in this case the fraction of the light transmitted depends upon the angle between the axes of the prisms, and is conveniently controlled by rotating one of the prisms, as described in Chapter IV.

Variants of the Grease Spot Photometer

The grease spot may be replaced by a wedge of plaster of Paris with its edge vertical and faces equally inclined to the light sources. Joly's diffusion photometer uses a block of paraffin wax cut into two halves and replaced together with a sheet of tin foil between them. This is placed between the sources so that each illuminates one part of the block. The observer watches the diffused glows in the blocks, and slight want of uniformity of the two halves is compensated for by repeating the balance with the block reversed.

Among the variants of the grease spot photometer, the Lumner-Brodhun photometer is the most sensitive. Light from the sources

strikes the diffusing surface SS in Fig. V. 3 on both sides, and the diffused light is reflected by mirrors M and M into the two glass prisms. The right-hand prism has a square hypothenuse face, while the similar face of the other has been ground away outside a circle on the face, so that when the prisms are put together, the area of contact is the unground circle. Light from the left-hand source passes through the circle of contact and illuminates the centre of the field view of the telescope T, while the light incident on the ground back surface is reflected back to the prism and lost. Light from the right-hand source is reflected back to the telescope over the region of non-contact, and illuminates the periphery of the field of view of the telescope while the light incident on the circle of contact is transmitted into the left-hand prism and lost. Adjustment until the field of view is uniform may be made by varying the distances of the sources or by using a variable standard, or by interposing filters.

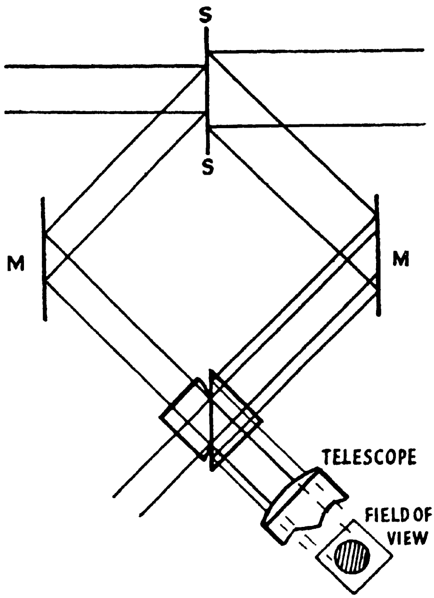


Fig. V. 3. Lummer-Brodhun photometer.

Flicker Photometers

The Abney Photometer (Fig. V. 4) may be taken as an example of this type. One source illuminates a fixed white screen AB while the other illuminates a rotating screen CD in the form of a Maltese Cross. The telescope views each screen in turn as CD rotates. If CD rotates at low speed and the surfaces are unequally illuminated, a

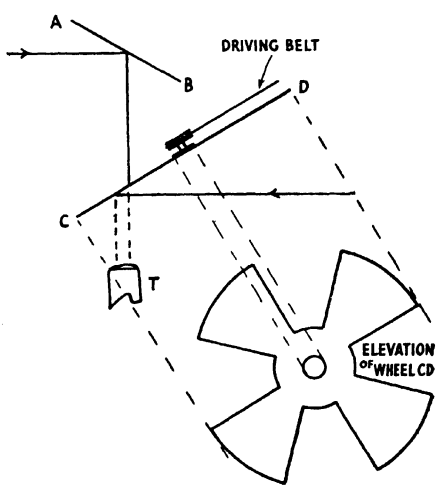


Fig. V. 4. Abney's flicker photometer.

flicker is observed. This flicker may be reduced if the intensities of illumination are equalised. The photometer is very successful in minimising the *difficulty of matching with* sources of different colours, for it happens that if sources varying both in intensity and in colour are observed by an eye in increasingly rapid succession, at first the eye observes the flicker of changing colour as well as changing intensity. At a higher speed the colour flicker disappears ; the eye observes a single tint of flickering intensity. This is the correct operating speed of the photometer, and the intensity flicker is banished by adjustment of the distances or by interposing filters. If the screen revolves too slowly, colour flicker prevents an accurate match, while if it revolves too fast, the intensity flicker is reduced, thus reducing the sensitivity of the adjustment. The proper speed for the screen depends upon the difference of the colours of the sources, and should be the lowest possible speed which gives a field of uniform hue.

A variant of this photometer is the Simmance-Abady Photometer, which employs a wheel of plaster of Paris whose edge is bevelled at 45° on each side (Fig. V. 5). The right-angled edge between these bevels, however, passes sinusoidally from side to side of the wheel as it goes around the wheel. Thus if the wheel is viewed from a point in its plane while it is slowly revolved, the observer sees sometimes more of the left-hand bevel and sometimes more of the right-hand bevel. If each edge is illuminated by one of the sources and the wheel revolved just above the speed needed for the colour flicker to disappear, an intensity flicker remains which is banished in one of the usual ways described above.

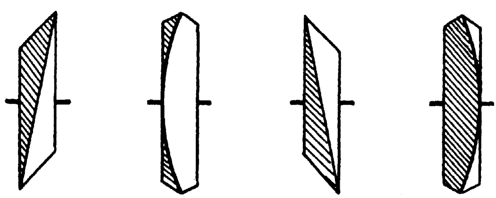


Fig. V.5. Elevations of Simmance-Abady flicker wheel.

Integrating Photometers

It has already been remarked that the candle-power of a source is its intensity in a particular direction. An electric pocket torch, for instance, has a large candle-power in the direction of its beam, and zero candle-power in any other direction. Thus the measurement of the candle-power in a particular direction gives no index of the total illuminating power of a lamp. One could, and in fact, often does, measure the candle-power in different directions, and so construct a "polar diagram" for a lamp. Such diagrams for an electric lamp, with and without a reflector, and for a candle, are shown in Fig. V. 6 where from a point, radii have been drawn proportional in length to the candle-power of the lamp in the direction of the radius, and the end points of these radii joined by a curve.

The total illuminating power of a source irrespective of direction is measured in lumens. The lumen is defined so that a source which has a candle-power of 1 in all directions, has a total illuminating power of

$4\pi = 12.6$ lumens. The *mean value of the candle-power* of a source may be found from a polar diagram, assuming the source to radiate symmetrically about the vertical; this value is called the mean spherical candle-power, and the value of the source in lumens is

$$\text{lumens} = 4\pi \times \text{mean spherical candle-power.}$$

The mean spherical candle-power, and therefore the lumen value of a source may be measured directly by an integrating, or mean spherical candle-power, photometer. A common form as used for measuring electric lamps, consists of a hollow sphere some 5 ft. in diameter, whitened inside, at the centre of which the lamp under test hangs. A small hole in the wall of the sphere has a telescope attached to it, by which a white screen hanging between the source and the telescope is observed. The side of the screen towards the telescope is therefore illuminated by light diffused from the walls of the sphere, and if the reflecting power of the wall is high, the illumination is an accurate measure of the mean spherical candle-power. Various methods for balancing the illumination against the standard are used. A standard source of light may illuminate a screen which is observed over half the field of view of the telescope. The intensity of the two halves of the field of view are then matched by inserting a neutral tinted wedge of glass in one of the beams, or by varying the voltage across the standard lamp. Or the filament of the standard lamp may be observed directly by the telescope against a background formed by the screen in the sphere. The voltage across the standard is then varied until the filament disappears, being neither duller nor brighter than the screen. This photometer needs calibrating by means of a lamp whose mean spherical candle-power has been measured by another method, say by calculation from the polar diagram. In this case it is not necessary to know what is the reflecting power of the walls of the sphere, but it should be noted that if this reflecting power is not high, the photometer will give poor results for a light source whose

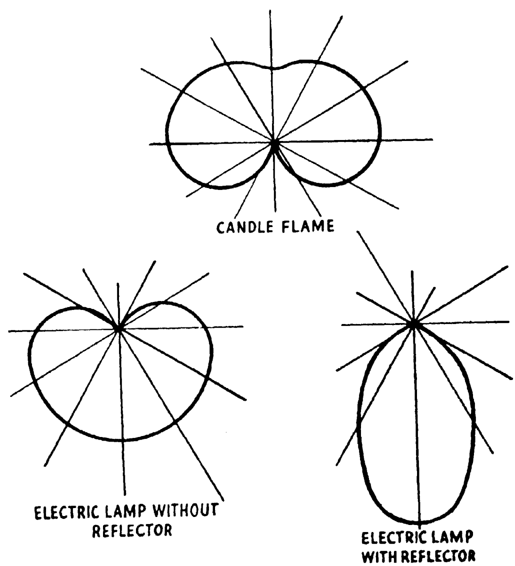


Fig. V. 6. Polar diagrams.

polar diagrams does not resemble the polar diagram of the source by which it was calibrated.

Colorimeters

The problem of measuring and specifying colours accurately has been satisfactorily solved only of fairly recent years. Modern colorimeters do this by one of two general methods.

As will be explained in Chapter VIII, white light is composed of an infinitude of pure spectral hues, but these do not comprise the whole gamut of colour sensations; for instance, pink, purple and brown are not spectral hues. If from white light any single spectral hue is abstracted, the remaining light is said to be of the complementary colour to the abstracted hue. It is found that any colour may be accurately matched, either by mixing white light with some spectral hue in due proportions, or by mixing white light with the complementary colour to that hue. This is the principle of monochromatic analysis upon which many colorimeters (e.g., the Nutting colorimeter) depend. White light from an electric lamp is split into two beams. One beam passes through a filter to control its intensity and illuminates a screen. The other passes through a prism to disperse its spectral hues. Either a stop is used to single out any spectral hue, or to arrest any hue (complementary) and the remaining light is recombined by passage through a prism with its edge reversed to the first one, and this light also falls on the same screen as the first beam. Control of the filter and the stop will allow the colour of this illuminated screen to match any desired colour placed beside it, and the resulting colour is specified by its dominant hue from the position of the stop in the dispersed beam, and by its purity (ratio of dominant hue to white light) by the degree of absorption of the filter.

The second general method depends upon the fact that any colour can be matched by a hue mixture of three primary colours (trichromatic analysis). Thus an instrument working on this principle will divide a beam of white light into three, will pass each beam through a primary colour filter (red, green and blue), and also through an intensity filter. Any colour is matched by an adjustment of the filters, and the colour is specified by the relative intensities of the three primaries. The common disadvantage of these systems is that each has a small range of colours from which matching is difficult or impossible, and special arrangements are often incorporated in colorimeters for dealing with these colours.

CHAPTER VI

RANGE-FINDERS

A range-finder is an instrument used to measure the distance usually from the place of observation to a target or object and in all forms it is essentially an angle measuring instrument in which the angles measured are converted into ranges.

Fig. VI. 1 shows the essential principle of all forms of range-finders. O is the observer and T the target, so that OT is the range it is required to measure. B is any other point and OB is called the base, then it is obvious that if we know the angle BOT and the length OB of the base, the distance OT can at once be found if we measure the angle BTO or the equal angle T^1BT where BT^1 is parallel to OT.

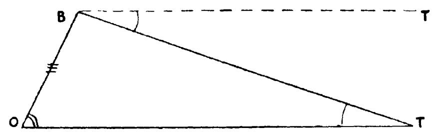


Fig. VI. 1. Essential principle of range-finder. OB is the base, and if the angles are known the triangle can be solved to find the range OT.

In most forms of range-finders the base OB is of fixed length and the angle BOT is a right angle ; in these circumstances the solution of the triangle for the length OT is very easy and can be made automatic.

Fixed Base Range-finders

In the early forms of fixed base range-finders, as for example in the "Telemeter," a piece of string of known length was the fixed base; at one end was an instrument used for setting the string at right angles to the line OT, and at the other end an instrument which measured the angle BTO and converted it automatically into a distance read on a scale. This form of instrument is now completely obsolete and has been replaced by the well-known tubular range-finders of rigid construction used very largely by all the fighting forces. In these instruments the length of tube or base may be anything from a few inches to 100 feet, although such large ones are not very common. The essential construction of such a range-finder is shown in Fig. VI. 2. M_1 and M_2 are two mirrors fitted at the ends of a tube of length B. Mirror M_1 is fixed so that the light from the distant object is reflected inwards at an angle of 90° to its original direction.

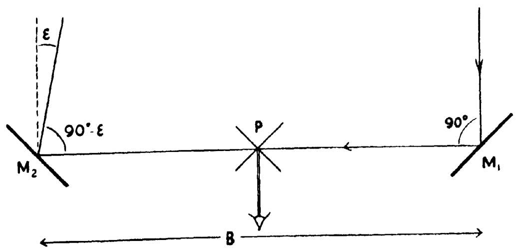


Fig. VI. 2. Principle of fixed base range-finder.

At P it is again reflected towards the eye by a mirror at P. The mirror M_2 may be capable of rotation, or on the other hand some other means may be used, as described later, to bring the ray from the distant object to the eye after it has been deviated through an angle $90° - E$. The angle E is a measure of the range, since B is fixed, and if the range is great in comparison with B we know that the range is given by the formula

$$R = \frac{B \times 3438}{E \text{ in minutes}} = \frac{B \times 206260}{E \text{ in seconds}}$$

In actual instruments mirrors are used only in the very smallest range-finders such as those fitted to cameras, while in large and precision instruments prisms are always used. The prisms at the ends of the tube to replace M_1 and M_2 are of pentagon shape known as Prandl or pentagonal prisms. A section of one is shown in Fig. VI. 3. These prisms have the property that the light is deviated exactly through a fixed angle depending only on the angle between the two reflecting surfaces, no matter how the prism may be rotated through a small angle. They are known as constant deviation prisms and a further property possessed by them is that there is no lateral inversion as there would be when there is only one reflection at a mirror. The mirrors at P are also replaced by more or less complicated prism systems depending on the style of the range-finder.

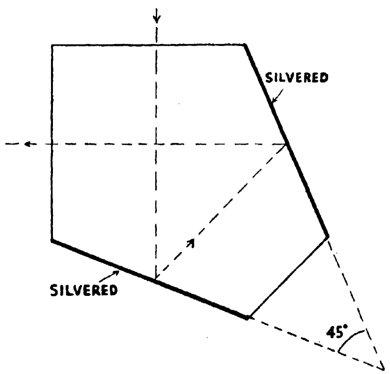


Fig. VI. 3. Pentagonal or Prandl prism.

Since we now have the two beams accurately bent through fixed angles, it is obvious that some additional means of adding a measurable deviation in one beam will be required. There are many ways of achieving this result, but they mostly depend on the deviations produced in a beam of light by a prism of small angle. Fig. VI. 4 now shows the stage of development in which two Pentags (pentagonal prisms) and a

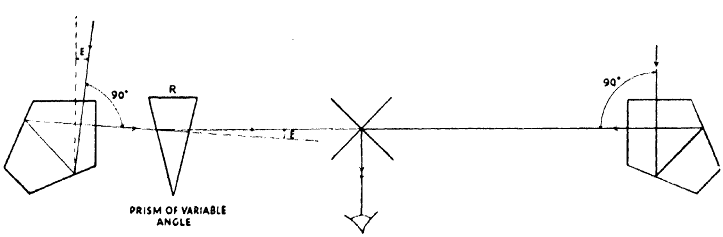


Fig. VI. 4. The prism R consists of two prisms of equal angle which are rotated in opposite directions so as to produce the effect of a prism of continuously variable angle.

prism R are used. The amount of deviation produced by the prism R must be variable and this can be achieved by placing two prisms of equal angle side by side and rotating them in opposite directions, giving in effect a prism whose refracting angle is continuously variable. The angle E of deviation will be related exactly to the amount of rotation so that a scale can be fitted to the rotating prism and engraved directly in range.

Since most range-finders have necessarily to be optical instruments having definite magnification and incorporating in effect telescopic systems, there must be parts of the paths where the light is converging

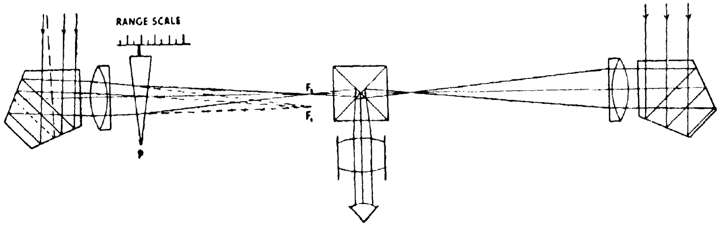


Fig. VI. 5. Form of modern range-finder. The prism P can be moved along the scale and the amount of the change of position of F depends linearly on the position of P.

towards an intermediate focal plane. Under these circumstances a prism with only a movement of translation can be used and Fig. VI. 5 shows finally the form which many modern range-finders take. It will be seen that we now have a pair of telescopes with a common eyepiece and with pentagonal prisms in front of the objectives to bend the rays inwards. The moving prism P travels along the axis of the telescope and its distance of movement can be made to indicate the range.

It will be seen that in the instruments so far described the two images from the ends of the base have been combined in a single eyepiece, and we have therefore either a superimposed field or a split field or a field with an inserted strip. All these methods have been used and in addition one field may be an inverted form of the other. There are advantages and disadvantages with all of them and in range-finders designed for special purposes one or other method may be found most practical. For fast-moving small targets, such as aircraft, the split fields and inverted fields are generally

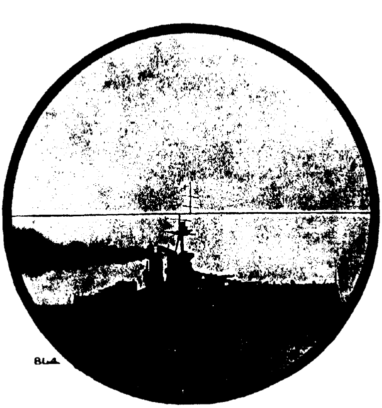


Fig. VI. 6. Field of view in split field range-finder. The range is measured when the mast appears to be continuous.

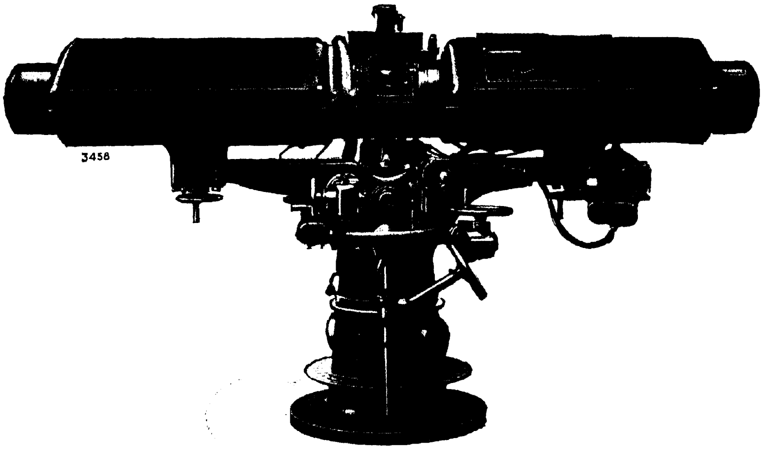


Fig. VI. 7. A modern range-finder.

unsatisfactory, and it is then often desirable to use a stereoscopic form of range-finder in which both eyes are used, and each eye sees one image, the two images being fused by the brain into a single image as in normal sight. In the field of the range-finder also is a floating mark by the adjustment of which the mark can be made to appear near or far away, and by making this mark appear to be at the same distance as the target, the range can be found. The use of stereoscopic range-finders is quite common but requires special training of the range takers. Fig. VI. 6 shows the appearance of a typical field of view as seen in a modern range-finder, and Fig. VI. 7 is a photograph of an actual range-finder.

Depression Range-finders

The base length of most of the range-finders described above is comparatively small, perhaps from 12 inches in portable instruments to 40 feet in large naval instruments or for coast defence, and attempts to make still larger based range-finders have not been altogether successful. In coast defensive works where batteries are often situated on cliffs some two or three hundred feet above sea-level, it is obvious that use can be made of this height as the base of a range-finder, and all that is required is an instrument capable of measuring accurately the small angle of depression to the target on the surface of the sea. The depression range-finder is one such instrument and in order that the angles of depression may be converted directly into ranges, use is made of the properties of similar triangles. In Fig. VI. 8 O is the observer and BT is the level of the sea at a given state of the tide. If we fix a scale SH at a distance below O it is obvious that by dividing this scale we can at once read a range by noting where the line OT cuts the scale.

In depression range-finders a telescope is mounted on a pivot at the eye end so that it can swing downwards and a sliding fitting under the telescope slides along a scale or range arm on which the ranges are read

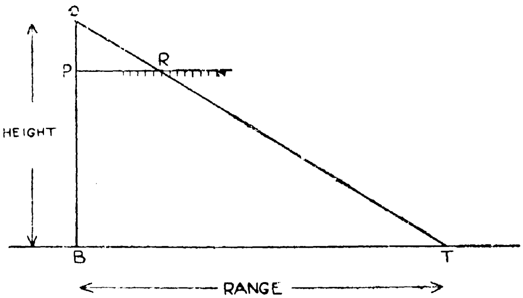


Fig. VI. 8. Principle of the depression range-finder. Triangles OPR and OBT are similar and therefore OP : PR = OB : BT. OP is a fixed fraction of the height OB and hence PR is the same fraction of the range BT.

directly. The range arm is compensated for the curvature of the earth and for the atmospheric refraction and the height between the telescope pivot and the range arm is capable of adjustment to allow for the state of the tide.

Stadia Methods

It is not always convenient to use either a fixed base range-finder or a depression range-finder and use is then frequently made of the reverse of the normal method, i.e., instead of observing a fixed point from opposite ends of a base, the eye is the fixed point and two points a known distance apart are observed and the angle between them measured. Thus in Fig. VI. 9 two wires in the field of view of a telescope

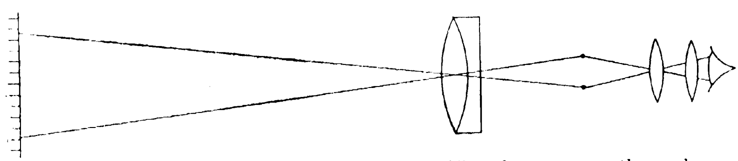


Fig. VI. 9. Stadia and subtense methods. The observer sees the scale and measures the number of divisions between two stadia in his eyepiece graticule. If the distance apart of the stadia and focal length of the object glass are known the range can be calculated. In subtense methods the ends of a rod of known length are brought successively on to a single cross wire and the angle of rotation measured.

are a fixed distance apart and by observing where these wires appear to intersect a staff a measure of the range is obtained.

This method is much used in surveying and many theodolites and levels are fitted with stadia wires in the graticule for this purpose. There

are many variations of the principle and another method known as the subtense method may be used if the telescope has no stadia wires. In the subtense method a bar of known length is held at the distant object whose range is to be measured, and the angle subtended by it at the eye is measured by the rotation of the theodolite. The technique of measuring such small angles accurately is well known to surveyors and will be found in text books on surveying.

It will be seen that the whole principle of range-finding is based on the measurement of a small angle. In aerial gunnery, for example, the span of the enemy aircraft can be guessed or known and made to fit between two stadia or marks on a sight thus measuring the range. Similarly, the known size of any object can be used as a base and a number of methods are available for measurig the subtended angle.

Echo sounding machines used by ships are essentially range-finders in which the time required for a sound wave to travel to the sea bottom and return is measured (see Chapter XXIII), and of course one of the simplest of all methods used for estimating range is to measure the time between seeing a flash of lightning and hearing the thunder, an interval of five seconds indicating a distance from the observer of approximately one mile.

CHAPTER VII

REFRACTOMETERS AND INTERFEROMETERS

An instrument of which the purpose is to measure the refractive index of a solid or liquid is known as a refractometer.

When a ray of light passes from air into a transparent medium, like glass, it is bent as shown in Fig. VII. 1. The ratio $\sin\alpha/\sin\beta$ is constant for all angles of incidence and is called the refractive index (μ). It is a fixed physical property of the material.

A knowledge of the refractive index of transparent solids and liquids is of importance for a number of reasons. The computing and manufacture of the optical systems of telescopes, microscopes, cameras and so on would be impossible otherwise. It provides a method of identification of pure liquids, since every substance has its own characteristic refractive index, and also it gives a quantitative estimate of the amount of dissolved solid in a liquid. For this latter purpose, preliminary measurements of the refractive index of the pure liquid and that of the liquid containing known concentrations of the solid are made. A linear relationship is generally obtained, so that the concentration is directly proportional to the increase in index. From this calibration a simple determination of the refractive index is sufficient to give the concentration directly, a process which with a suitable instrument takes only a few moments. It thus eliminates the necessity of lengthy chemical analysis, so that a manufacturing process does not need to be held up. A refractometer is now an essential tool in almost all chemical laboratories, whilst it is indispensable in the sugar, jam, beer, wine, spirit and other industries.

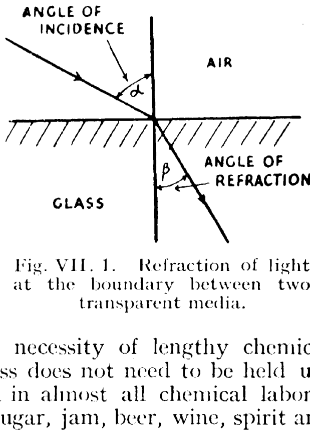


Fig. VII. 1. Refraction of light at the boundary between two transparent media.

The Spectrometer

The most accurate refractometer, but not the most useful commercially, is the spectrometer, shown diagrammatically in Fig. VII. 2. It consists of a fixed collimator, containing an achromatic lens at the focus of which is a fine, vertical slit, producing a parallel beam of light. This falls on to a glass prism of refracting angle about 60°, the refractive index of which it is desired to measure. The resultant refracted and deviated parallel beam is received by a telescope which forms an image of the collimator slit in the focal plane of the telescope coincident with the crosswire. This is arranged to be in the focal plane of the eyepiece, so that a magnified image of the crosswire and slit is seen by an eye looking through the telescope eyepiece. The telescope rotates about the axis of a hori-

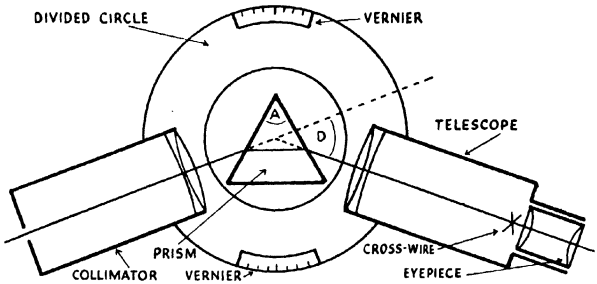


Fig. VII. 2. Essentials of a spectrometer. A = Angle of the prism. D = Angle of minimum deviation.

zontal divided circle and its position on the circle is read by two verniers, which are rigidly attached to the telescope mounting and rotate with it. The prism rests on a table which can be clamped to the divided circle and rotates with the circle. Thus the relative rotation of the prism and the telescope may be measured.

The formula from which the refractive index may be calculated is $\mu = \dfrac{\sin \frac{1}{2}(A + D)}{\sin \frac{1}{2} A}$ where μ is the refractive index of the glass relative to air, A the angle of the prism and D the angle of minimum deviation.

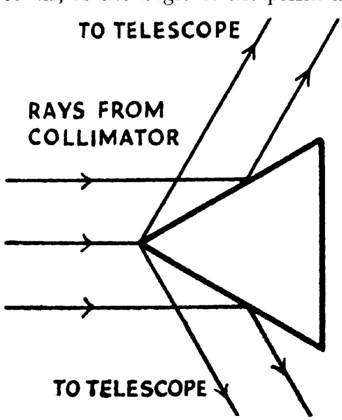


Fig. VII. 3. Measurement of prism angle A.

The angle of the prism is measured by the method shown in Fig. VII. 3. Light from the collimator is reflected simultaneously by the two polished faces of the prism, and received by the telescope in the positions shown, the angle between which is twice the angle of the prism. To obtain the angle of minimum deviation the prism when approximately in the symmetrical position shown in Fig. VII. 2 is slowly rotated in one direction by the fine adjusting screw. As the position of minimum deviation (which is accurately symmetrical) is passed through, the image of the slit moves across to the right, reaches a limiting position, and then moves back to the left. This limiting position of the image of the slit defines the setting for the minimum deviation, and can be made with great accuracy. The prism is then removed and the telescope rotated so that the light from the collimator passes straight into it, the angle of rotation being the angle of minimum deviation.

In small instruments the circle may be 5 inches in diameter and reads by vernier to 1 minute of arc, whilst in better instruments with larger circles and more finely-divided scale, readings may be made by

vernier to 10 seconds of arc, or better. This enables the refractive index to be measured to about 1 part in 100,000.

If the refractive index is required for a number of different colours it is only necessary to use a light source giving the various colours, and to measure the minimum deviation for each.

For finding the refractive index of a liquid the liquid is put into a hollow glass prism, the sides of which are made wholly or in part of plane parallel glass plates cemented together. The procedure is exactly the same as described above with the solid prism, and the arrangement is equivalent to a liquid prism. It is the most accurate method for liquids, but not the most convenient.

Abbe Auto-Collimation Spectroscope

This is a modification of the above method in which a 30° prism is used, and in which the telescope also serves as collimator (Fig. VII. 4). In the upper half of the focal plane of the eyepiece is a slit into which light enters by a hole in the side of the tube reflected by a small 45° prism. In the lower half of the field is a sharp pointer. In use the prism table is rotated until the light refracted at the first face of the prism meets the second face normally, and is returned along its own path to form an image of the slit in the focal plane of the telescope, coinciding with the pointer.

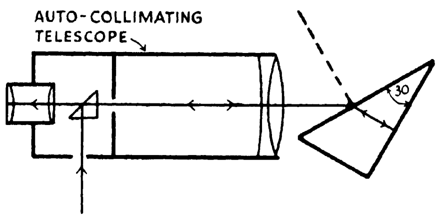


Fig. VII.4. Abbe auto-collimation spectroscope.

It is clear from the diagram that $\mu = \dfrac{\sin i}{\sin A}$ since the angle of refraction is equal to the refracting angle of the prism.

The angle i is found by rotating the telescope until it is normal to the first face of the prism. The refracting angle of the prism A is determined by rotating the telescope into the two positions in which it is normal to both surfaces of the prism.

The Abbe spectroscope has the advantage over the normal type in that no collimator is required and only half as much glass as in a 60° prism is necessary. A hollow glass 30° prism is used for liquids.

For industrial purposes the spectrometer method of measuring refractivities of solids and liquids has the disadvantages that a determination takes an appreciable time, computation is necessary, a substantial quantity of liquid is required, and two first-class optically plane surfaces of the solid are necessary.

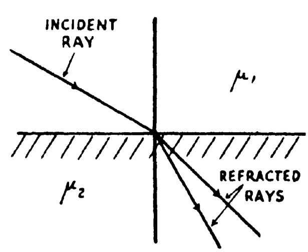


Fig. VII. 5. Diagram showing how rays in medium μ_2 are confined between the normal and the critical angle, when μ_1 is greater than μ_2.

For these reasons the critical angle type of refractometer is used in which one setting only is required, and in which the refractive index may be read off directly on a scale.

Theory (Fig. VII. 5). For an angle of incidence of $\pi/_2$ it is clear that

$$\frac{\mu_2}{\mu_1} = \frac{\sin \pi/_2}{\sin \alpha_c} = \frac{1}{\sin_c} \quad \text{or } \underline{\mu_1 = \mu_2 \sin \alpha_c}$$

Thus if μ_2 is known, μ_1 is obtained by the measurement of α_c only. This can be done accurately for light can only enter medium μ_2 between the normal and the direction of the critical angle. Thus there will be a sharp boundary, one side of which is bright and the other dark, so that by suitable arrangement of the optical system an accurate setting may be made.

The Pulfrich Refractometer

This is an instrument of the critical angle type. In its modern form it uses a 60° prism, the top and the working side face being optically flat and polished, with the top edges bevelled into a circular rim. For liquids (Fig. VII. 6) a circular glass tube is cemented to the block with a cement or wax which is not soluble in the liquid to be examined. In its application to solids (Fig. VII. 7) the specimen is prepared with polished faces, one 2-3 cm. long and accurately flat, and the other, which should be approximately perpendicular to the first, need only be of secondary quality, but it must intersect the first surface in a clean sharp edge. A very thin film of liquid of higher refractive index than the specimen is interposed between the two glass surfaces to obtain optical contact.

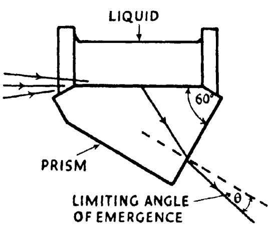


Fig. VII. 6. Pulfrich refractometer for liquids with 60° prism.

A convergent beam of monochromatic light is directed along the interface and the emergent light is received by an auto-collimating telescope focused for parallel light. The field of view is divided into two sections with a sharp dividing line, one section being bright and the other dark. The cross-wires of the telescope are set on this dividing line, and the angle θ measured on the vertical scale, which is read by vernier to 15 seconds of arc. To avoid having to place the head in inconvenient positions, the telescope has a right-angled prism behind the object glass, so that the main body of the telescope is horizontal.

The path of the light is shown, the formula for computation being:

$$\mu_1 = \sin\ \theta\ \sqrt{\mu_2{}^2 - \sin^2\ \theta} + \sin\ \theta \cos A$$

The angle A of the prism may be measured *in situ* on the instrument, by using the auto-collimating telescope and measuring the angle between the normals of the polished faces, and the refractive index (μ_2) by measuring the angle of minimum deviation in the usual way. Incidentally, this is a great improvement on the older models of the Pulfrich, which utilised a 90° prism in the form of a solid cube, in which neither the angle nor the refractive index could be measured directly. The correctness of the 90° angle had to be assumed, while the refractive index was that given by the makers for a representative

sample, which could differ slightly from the actual prism used.

The only subsequent measurement necessary for any specimen, liquid or solid, is the angle θ, which requires one setting only, so that the required refractive index (μ_1) may either be calculated or tables may be provided from which the index may be read off for any value of θ. The accuracy possible is one unit in the fifth decimal place.

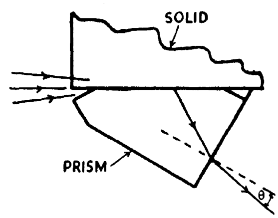


Fig. VII. 7. Pulfrich refractometer for solids with 60° prism.

In small instruments of high accuracy, temperature control is important, and this is provided by surrounding the prism and specimen with water jackets through which thermostatically controlled water, usually at 20° C., is circulated.

Abbe Refractometer

This is another type of critical angle refractometer which is made only as a direct reading instrument calibrated by the manufacturers. The optical system (Fig. VII. 8) consists of two similar prisms of suitable glass placed very nearly in contact, and held in position by hollow brass castings, through which thermostatically controlled water can circulate. A few drops of the liquid to be tested, the index of which must be lower than that of the glass, are placed upon the matt surface of the lower prism which is hinged so that on closing the box the liquid is squeezed into a thin parallel film which fills the small space between the prisms. The mirror below the prism box is then inclined in such a way that light is directed on to the lower prism normally. It strikes the matt surface and is scattered into the liquid film and the upper prism. No ray can enter the upper prism with a greater angle of refraction than that of the ray at grazing incidence. The emergent rays are collected by a telescope focused for parallel light. The field of view will be divided into dark and bright portions with a sharp dividing edge on which the cross wires of the telescope are set. In one form of instrument the prism system is fixed and the telescope rotated, in another the telescope is fixed and the prism box rotated. In both instruments

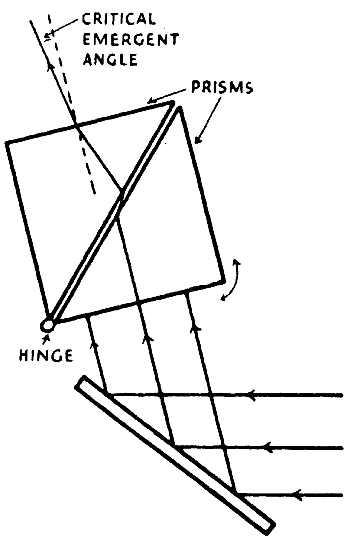


Fig. VII. 8. Optical system of Abbe refractometer.

the index is read off directly on a graduated arc, to one unit in the fourth decimal place.

The instrument may also be used with white light, in which case the dividing edge would consist of a band of colour owing to the dispersion of the system (variation of refractive index with colour or wavelength). This is neutralised by a compensator, consisting of two direct vision prisms which are rotated at equal rates in opposite directions by turning a milled ring, and thus giving a black and white field. The reading of the compensator scale gives the dispersion by reference to a table supplied with the instrument.

For *solids* the lower prism is removed, and a specimen similar to that employed in the Pulfrich refractometer is placed against the surface of the lower prism, optical contact being obtained by a film of liquid of higher index than the specimen.

The Abbe is usually designed to give the index from 1.3000 to 1.7000, correct to one or two units in the fourth place and is in very general use in the oil, fat, sugar and jam industries. For sugar solutions, fruit pulps, etc., an additional scale is provided reading directly the percentage of total solids in such solutions.

There are many other specialised types which depend on the principles discussed. The *Abbe Crystal refractometer* is an adaptation of the Pulfrich principle, enabling the index of crystals and precious stones to be determined. The *Immersion refractometer* and the *B. & S. projection refractometer* are similar in principle to the Abbe refractometer, the former for liquids available in fairly large quantity, as in the beer, wine and alcoholic industries, whilst the latter is designed specially for viscous, dark-coloured, transparent or translucent materials. The *differential refractometer* measures minute differences of index between liquid solutions of slightly different concentration.

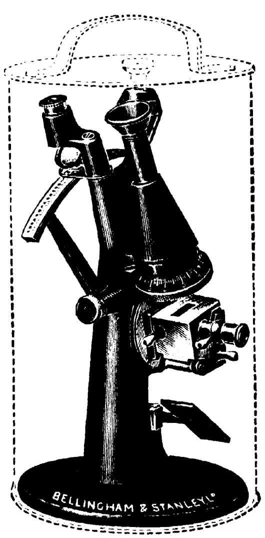


Fig. VII. 9. Abbe refractometer.

Interferometers

All interferometers depend on the principle of superposition applied to light vibrations. Thus suppose that due to a single wave train we have a displacement X in a given direction at a certain point and time, and that due to another train acting by itself we have a corresponding displacement Y, then the *instantaneous* resultant displacement R of the two waves acting together is the algebraic sum of the separate displacements: $R = X + Y$.

Fig. VII. 10 shows this principle applied to two sine vibrations of the same frequency or period, each representing the variation of displacement at the same point with time. Fig. VII. 10a shows the resultant vibration at the point when they are *in phase*, i.e. both vibra-

tions reach their maximum displacement positive or negative, at the same instant. Fig. VII. 10b shows the result when the two vibrations

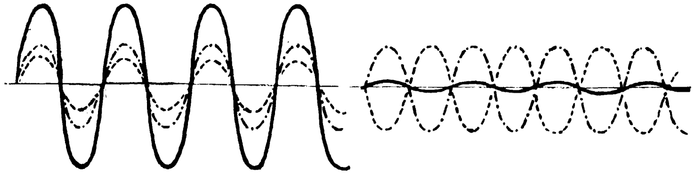


Fig. VII. 10a. Fig. VII. 10b.
Illustration of principle of interference.

are out of phase, i.e. the maximum positive displacement of one vibration occurs at the same time as the maximum negative displacement of the other. It is clear that if the two amplitudes (maximum displacements) were equal, the result would be no vibration whatever at that particular point. Comparing Fig. VII. 10b with Fig. VII. 10a, it is clear that one vibration is shifted relative to the other by one-half a period. A shift of any exact number of periods would produce exactly the same effect again as in Fig. VII. 10a, whilst an additional shift of an extra half a period would produce the effect of Fig. VII. 10b.

Interference with Slits

Fig. VII. 11 illustrates the effect that would be produced by two light sources of the same period, from which light is spreading out in all directions. Consider a plane perpendicular bisector of the line joining the two sources. At a point such as O, $S_1O = S_2O$; consequently the waves from the two sources arrive at O in phase, thus producing increased brightness (as compared with one source only).

At a point such as Q there is a path difference between the sources of $S_2Q - S_1Q$ so that the resultant intensity will depend on the phase difference so produced. For a path difference of a whole number of wavelengths, corresponding to a whole number of periods, they will be in phase, so producing an increase of brightness, whilst for an additional path difference of a half wavelength, corresponding to an additional half period, they will be out of phase, so producing a decrease in intensity, or zero intensity if the two sources are of equal intensity. For other path differences the intensity will have an intermediate value. The illumination in this plane will therefore consist of a series of vertical bright and dark bands or fringes, which because of the very small size of a wavelength of light (4 to 7.5×10^{-5} cm.) will be equidistant and close together. From one bright or dark fringe to the next the path difference increases by one wavelength.

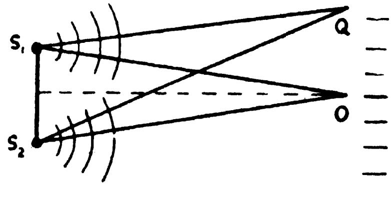


Fig. VII. 11. Interference with two slit sources.

In practice it is impossible to use two independent light sources, so that the experimental arrangement is such that one light source only is used which by some optical device is virtually split up into two, so that a path difference can be produced.

The Fresnel Biprism, Lloyd's Mirror, Fresnel Double Mirror, Billet Split Lens, and the Rayleigh Interference refractometer are examples. Of these the Rayleigh instrument and its modifications only will be described. The others are of historical interest only, in that they represented the first method whereby a good approximation to the true wavelengths of light was obtained.

Rayleigh Interference Refractometer

This was originally designed to measure the refractive index of gases, which differ only very slightly from unity. Parallel light from a collimator divided into two beams by the two slits (Fig. VII. 12), passes through two tubes usually about 100 cm. long, closed by optically worked glass plates. On emergence they are brought together in the focal plane of the telescope producing very fine equidistant vertical fringes which are viewed through a high power eyepiece.

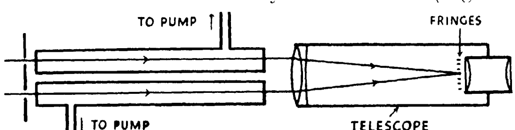


Fig. VII. 12. Rayleigh refractometer.

The method of working may be understood as follows. Suppose both tubes are initially completely evacuated. Now allow the gas under test to pass slowly into *one* of the tubes. This increases the optical path, by which is meant the total number of light waves in the path. A distance L in a medium of refractive index μ will have the same number of waves as (or is optically equivalent to) a distance μL in a vacuum, since the ratio of the wavelength in a vacuum as compared with the wavelength in the medium is as $\mu : 1$. μL is the optical path. Thus the fringes will move across the field of view and may be counted to within $\frac{1}{40}$ fringe. A shift from one fringe to the next means a change of path of one wavelength (λ). If the number moving across is n, the path difference is $n\lambda$. Also if the length of the tube is L, and μ the refractive index of the gas, then the path difference can also be expressed as $(\mu - 1)\, L$, so that $(\mu - 1)\, L = n\lambda$. Since n, λ, and L are known, $\mu - 1$ and therefore μ can be calculated. Thus for oxygen at atmosphere pressure $\mu - 1 = 0.0002728$, or $\mu = 1.0002728$, an accuracy of one part in 10 million.

For industrial use the instrument is provided with a calibrated compensating device placed between both tubes and the telescope, movement of which restores the band system to its original position and gives directly the *difference* in refractivities of the gases in the two tubes. It is used in this way for determining the percentages of impurity in a mixture. For example it will detect the presence of 0.01% of hydrogen in air, 0.04% of water vapour, 0.01% carbon dioxide, 0.03% carbon monoxide, 0.034% sulphur dioxide, 0.003% chlorine, and so on.

Portable types are made in which the tube length is reduced by using multiple reflection. These are used for example, in testing the permeability of balloon fabrics to hydrogen, in the quantitative analysis of flue gases, and in the testing for fire damp (methane) in coal mines.

Application to Liquids

Because of the much greater refractive indices of liquids as compared with gases, the length of tubes required, need only be from 1 mm. to a maximum of 10 cm., the small sizes being used when an absolute value of the index is required (relative to air), the larger sizes being used when a comparison between two liquids of almost the same index is required, such as the estimation of the salinity of sea water, and the concentration of salt solutions, in which a higher accuracy is obtainable than by laborious chemical analysis. Another interesting application is in the testing of the blood sera of children.

Interference without Slits

Interference effects may also be obtained in another way which has very important applications, the principle of which is illustrated in Fig. VII. 13. A ray of light ① incident on a film is split up into two rays, one reflected from the front surface, ② and one from the back ③. (The rays shown separately in the diagram are actually coincident.) The path difference between these two reflected rays is $2t$, twice the thickness of the film. If $2t = n\lambda$, increased brightness results, whilst if $2t = n\lambda + \frac{1}{2}\lambda$, the brightness is reduced. If the film is wedge-shaped as in Fig. VII. 14, then with monochromatic light (of one wavelength only) equidistant bands of light will be seen, the spacing being such that $d = \lambda/2\alpha$. To see these bands the eye or optical instrument must be focused on the film, and the illuminant must be an *extended source*. These are often called localised fringes. It is clear that the greater the wavelength the greater the spacing of the bands. The red bands will have nearly twice the spacing of the violet. It follows that with white light coloured bands will be seen, since at a given point some colours will be missing. These colours, however, are only seen if the film is very thin indeed, of the order of a few wavelengths, say about one twenty thousandth of an inch. The colours seen on oil films on roads, and of soap bubbles are examples. With monochromatic light bands may be seen with considerable thicknesses of film.

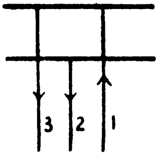


Fig. VII. 13.
Interference by a film.

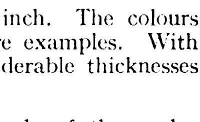


Fig. VII. 14.
Interference by a wedge.

The formula $d = \dfrac{\lambda}{2\alpha}$ also tells us that as the angle of the wedge decreases, the spacing of the bands increases, until if the film is strictly parallel, so that $\alpha = 0$, uniform illumination obtains.

If, however, a telescope focused for parallel light is used a system of circular bands may be seen in the focal plane of the telescope

objective. Fig. VII. 15 indicates how these are produced. The effect of the reflections is as if there are virtual sources behind each other. The rays reflected at an angle θ will have a path difference of $2t \cos \theta$

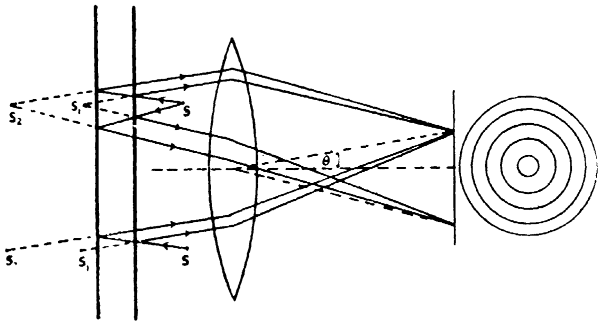


Fig. VII. 15. Circular fringes produced by a parallel film.

($2\mu t \cos \theta$ if medium has an index μ), so that there will be brightness or darkness for different values of θ. This applies to all points of the *extended source,* all the reflections at a given angle θ having the same path difference and coming to a focus at the same point in the focal plane. The complete picture is obtained by rotation about the axis of the telescope, so that a system of concentric circular bands is produced, which are wide apart if t is small, and close together if t is large. If we imagine the distance between the reflecting surfaces gradually increasing, the bands would close in towards the centre.

A similar set of circular fringes would be seen by transmitted light.

Fabry-Pérot Interferometer

This utilises a pair of glass or quartz plates, one of which may be movable. They are adjusted by suitable screws to be accurately parallel and produce circular fringes by transmitted light in the manner described above, being equivalent to an air plate the thickness of which may be varied. There is one important difference. The inner surfaces of the plates are silvered to such a degree that only a small proportion of the light is transmitted at each reflection, the remainder being internally reflected. As a consequence there may be as many as forty or more visible images formed which results in the bright bands being very narrow. A very accurate slide actuated by a fine screw, controlled by a worm, gives the necessary delicacy of movement of the mirror.

This instrument has two important functions, the details of which will have to be omitted. First the accurate determination of a wavelength of light. It will be appreciated that a movement of the mirror such that one band takes the place of its neighbour means a change of path of one wavelength. For the central band this corresponds to a movement of the mirror of half a wavelength. By an extension of this principle it is clear that any length may be found in terms of the equivalent

number of wavelengths. Because of the sharpness of the bands, a distance equivalent to a hundredth of a wavelength can be estimated by this instrument. In this way the number of waves in a distance of 1 metre is found to be 1,553,164.13, to an accuracy of at least 1 part in 10 million, using the pure red line given by a cadmium arc. This means that the wavelength of light may now be considered as the primary invariable standard of length. Furthermore this wavelength also forms the standard against which all other wavelengths are compared, and the Fabry-Pérot interferometer may also be used for the accurate comparison of wavelengths.

Secondly, the instrument is used for the determination of fine structure of spectral lines which is of great importance in modern atomic theory. For example, the well-known green line of mercury is found to consist of a number of components very close together. Here again the sharpness of the bands due to the silvering of the inside surfaces of the plates is the important factor in enabling the instrument to resolve the fine structure.

The Lummer-Gehrcke plate is another type of interferometer particularly adapted to the determination of the fine structure of spectral lines, which uses the principle of multiple reflection at the optically flat sides of a parallel glass or quartz plate.

The Michelson Interferometer

Fig. VII. 16 shows a simplified diagram of the interferometer. Light from an extended source is divided at the back half silvered surface of an optically plane parallel plate of glass, into two beams which fall normally on the fully silvered mirrors. The returned beams reunite at the same half-silvered surface and enter the observing telescope. It is clear that the effect of the half-silvered mirror is as if mirror M_1 were situated at M_1, so that if M_1 and M_2 are parallel we have exactly the optical system of Fig. VII. 15 and the bands are a series of concentric rings. They differ from the Fabry-Pérot bands in that since only two images of the source are formed, the bright and dark bands are of equal width. This ring system is formed for quite large path differences. If, however, the path difference is small, then *localised* straight line fringes may be obtained if the surfaces are not quite parallel. If, moreover, the surfaces intersect, the localised straight line fringes are obtained with white light, consisting of a *black fringe at the position of zero path difference*, with three to four coloured fringes at either side. The use of these "coloured" fringes with white light enables the position of zero path difference to be accurately determined. The movement of mirror M_2 is governed by the same mechanism as is the Fabry-Pérot interferometer. It also lends itself to an absolute determination of the metre. One of the most important applications of the instrument from the purely

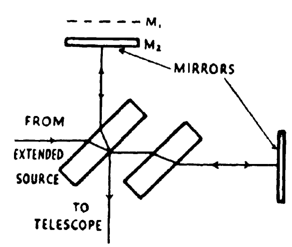


Fig. VII. 16. Optical system of Michelson interferometer.

scientific point of view was in the famous Michelson-Morley experiment, which was designed to measure the velocity of the earth relative to the

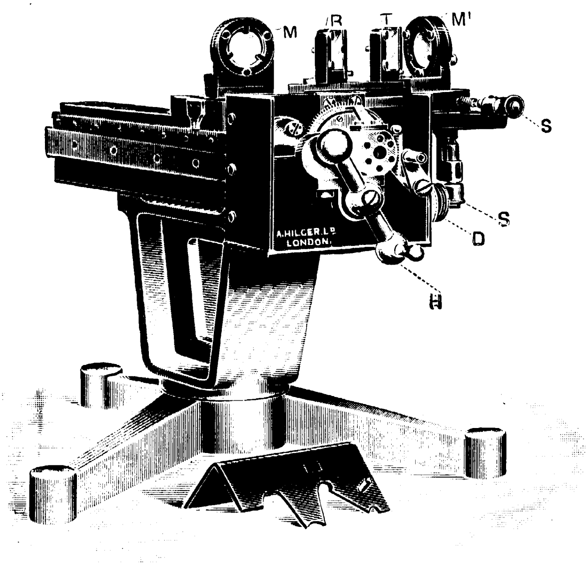


Fig. VII. 17. Michelson interferometer.
M and M¹—fully silvered mirrors. R—half silvered mirror.
T—compensating plate. SS—fine adjusting screws to M¹.

so-called "Luminiferous Ether." To everybody's astonishment, the answer was zero. As a consequence of this and other experiments which followed, the Relativity Theory of Einstein was born, which created a revolution in thought in the domain of Physics with important repercussions in Philosophy.

Zeiss Gauge Testing Interferometer

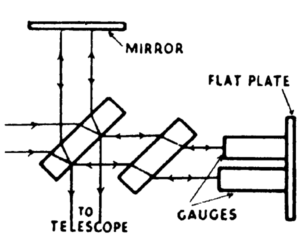


Fig. VII. 18. Zeiss gauge testing interferometer.

This applies the principle of the Michelson Interferometer, and is shown in Fig. VII. 18. The mirror M_1 of the Michelson is replaced by an optically flat plate on which the gauges are 'wrung,' i.e. pressed into optical contact, using oil as lubricant. Two sets of fringes are seen side by side, each covering half the field of view, the fringes of one set being displaced relative to those of the other set. By estimating the fringe displacement

to one-tenth of a fringe, the gauges may be compared to within a millionth of an inch. By using the method of fractional parts with a number of selected wavelengths the absolute length of a single gauge may be determined.

The only disadvantage is that the process of 'wringing' inevitably entails some slight wear of the standard.

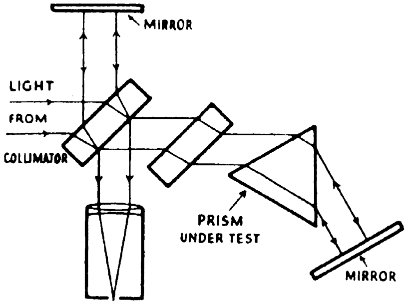


Fig. VII. 19.
Optical system of Hilger prism interferometer.

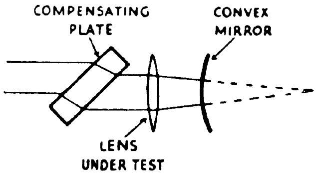


Fig. VII. 20.
Optical system of Hilger lens interferometer.

The Hilger Prism and Lens Interferometer

The general arrangement, which is similar to the Michelson Interferometer, is shown in Fig. VII. 19 and Fig. VII. 20. In Fig. VII. 20 the prism and plane mirror of Fig. VII. 19 is replaced by the lens and convex mirror. Instead, however, of the extended source used by Michelson, a collimator with a small circular diaphragm is used, so that a sensibly

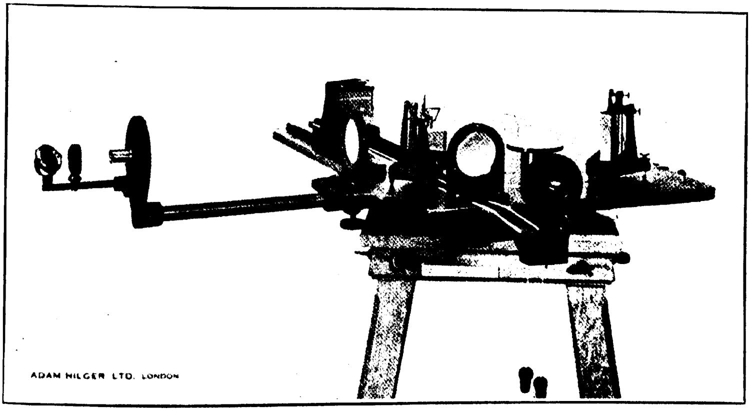


Fig. VII. 21. Hilger prism and lens interferometer.

parallel pencil of light is produced, emanating therefore from a very small source. The focal length of the collimator lens is such that an eye suitably placed behind the diaphragm can focus on to the mirrors. If the prism or lens is perfect, a plane wave entering the component will emerge after reflection as a plane wave, so that since the mirrors are accurately parallel, the interference pattern will consist of a uniform field of view, as the path difference is the same everywhere. If, however, the prism or lens is imperfect, then the resultant field produces an interference pattern which looks like, and may be regarded as a "contour map" of the imperfections. By local polishing superfluous material can be removed from the prism or lens. In this way an optically perfect component can be produced from inferior glass.

This instrument is in use all over the world, and has been modified so that complex lens systems, such as camera lenses and microscope objectives may be tested and corrected. In addition it forms a very sensitive research tool in numerous problems of all kinds.

Hilger Gauge Testing Interferometer

An improved gauge testing interferometer designed by Adam Hilger (Fig. VII. 22), based on the Michelson Interferometer, has the important

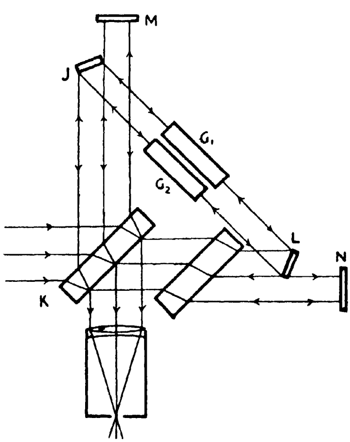


Fig. VII. 22. Hilger gauge testing interferometer.

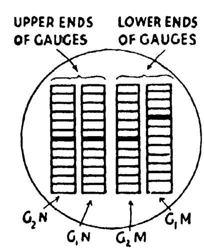


Fig. VII. 23. Appearance of fringe system.

advantage that no actual mechanical contact is made at either end of the gauges, so that the master gauge is not subjected to wear of any kind. Furthermore, it is possible to measure absolutely the length of the master gauge.

It is similar in principle to their Prism and Lens interferometers. A sensibly parallel pencil of light is divided in the usual way at a half-silvered mirror. Considering the lower half of the half-silvered mirror K, the transmitted light passes to the mirror N, where it is reflected back along its own path, whilst the reflected light is reflected by the

45° mirror J on to the ends of the two gauges G_1 G_2, from where the light is reflected back along its own path. The positioning of the mirrors and gauges are so adjusted that these paths are equal, so that when these are recombined they form fringes with white light as shown in Fig. VII. 23. When the central black fringe is continuous in both surfaces this pair of surfaces of the gauges must be identically in the same plane. Now considering the top half of the half-silvered mirror K, the reflected light passes to the mirror M, and is reflected back along its own path, whilst the transmitted light passes to the mirror L, is reflected to the other ends of the gauges, and is then reflected back along its own path. These two beams also reunite forming a similar interference pattern. If the gauges are not quite of equal length the appearance of the field of view may be somewhat as in Fig. VII. 23. The number of bands and fractions of a band by which the fringe system is displaced is measured, giving directly the difference in length to a millionth of an inch. By suitably tilting the mirrors M and N, the spacing of the fringes may be adjusted to any value. Increasing the tilt increases the number of fringes in the field of view. Using the fractional band method with a number of selected wavelengths, and a special reference gauge, the absolute length of a gauge may be determined.

Other modifications of this instrument made by Adam Hilger enable the angles of angle slip gauges to be checked against a standard to within a small fraction of a second of arc.

CHAPTER VIII

SPECTROSCOPES, X-RAY SPECTROGRAPH and MASS-SPECTROGRAPH

The Spectroscope

The function of a spectroscope is to sort out the different kinds of light emanating from a luminous source. The resultant appearance is called a spectrum, and may be photographed or observed visually. There are two main types of instrument for producing such spectra. One utilises the Prism, and is called a Prismatic Spectroscope; the other utilises the Diffraction Grating and is known as a Grating Spectroscope. If designed to produce a photograph of the spectrum, the instrument is then known as a Spectrograph.

The Prism

The use of a prism depends upon the experimental fact that different colours are deviated (or refracted) by different amounts on entering or emerging obliquely from one optical medium into another. This important result was first investigated by Sir Isaac Newton (1642-1727) in 1672, who proved by his crossed prisms experiment that natural white light is made up of all the rainbow colours, red, orange, yellow, green, blue and violet, superimposed.

Fig. VIII. 1 shows how a ray of white light is split up by a prism, into its constituent colours, proceeding after emergence in different directions. This is the essential factor which gives the prism its importance and enables it to separate out the constituent colours. The essential parts of a simple prismatic spectroscope are represented in Fig. VIII. 2. Light from the source enters through a narrow slit placed at the focus of an achromatic lens, producing parallel light, an arrangement known as the collimator. The different constituents of the source on emergence from the prism produce parallel bundles of rays of different inclination. A second lens collects each differently-coloured parallel bundle and forms an image of the original slit in its focal plane, one for each constituent of the original light, at different points in the focal plane. Thus there will be as many images as there are different colours or wavelengths in the original light. This pattern of images is called a spectrum (Fig. VIII. 3). It may be viewed with an eyepiece or it may be photographed, the plate or film being placed in the focal plane of the telescope objective, in which case the instrument becomes a spectrograph.

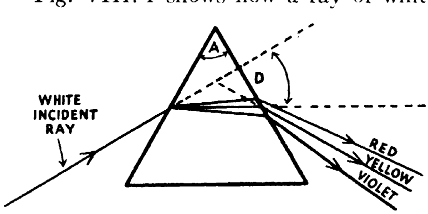


Fig. VIII. 1. Passage of white light through a prism.

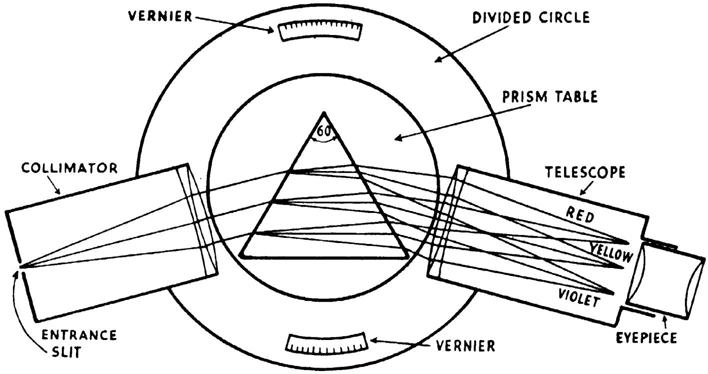


Fig. VIII. 2. Simple Spectroscope.

Types of Spectra

Spectra are of two main kinds, (1) Emission Spectra, (2) Absorption Spectra.

The first type is produced by self-luminous sources, and may consist of a continuous spectrum, or a line spectrum. The former is produced by incandescent solids or liquids, and contains all possible wavelengths, so that the spectrum is spread out into a continuous band. It follows that substances in this state cannot be distinguished from each other. When the substances are in the state of luminous gas or vapour, they emit line spectra, consisting of groups of discrete wavelengths, which are characteristic of that particular substance, and by which it can be accurately identified.

When many non-luminous solids, liquids or gases are placed between a continuous light source, such as an incandescent electric lamp, and the entrance slit of the collimator of a spectroscope, the continuous spectrum is found to be crossed by one or more dark bands, generally broad. Such non-luminous solids or liquids absorb certain colours and allow others to pass through. The resultant *absorption spectrum* is found to be characteristic of these substances and forms a definite means of identification.

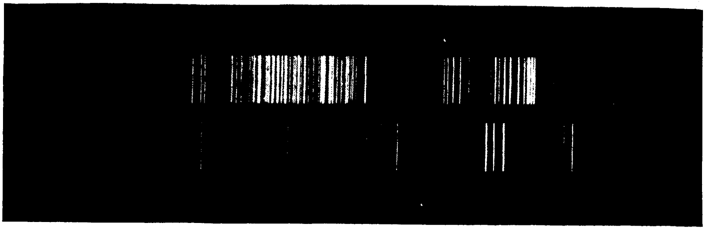


Fig. VIII. 3. Typical line spectra. Top, iron arc. Bottom, copper arc.

It follows from what has been said that the usefulness of any spectroscope depends upon the identification of the wavelengths of the bright lines in a line spectrum and the dark bands in an absorption spectrum. All prismatic spectroscopes have to be calibrated with known lines (or wavelengths) and different methods are adopted in different instruments to enable the user to read off the wavelengths either directly, or by reference to a calibration chart.

The simple prismatic spectroscope (Fig. VIII. 2) consists of a fixed collimator, a divided circle about the axis of which the telescope rotates, and the position of which is read off on the circle by the verniers. The prism rests on a table which can also be rotated about the axis of the divided circle. Usually the telescope and the divided circle rotate together, while the prism and verniers rotate together.

The most accurate method of use of this instrument for the comparison of wavelengths is to measure the angle of minimum deviation (D, Fig. VIII. 1) for a number of standard wavelengths, and to construct a calibration chart, from which any unknown wavelengths may be measured by interpolation. A ray passes through the prism at minimum deviation when it is symmetrical. Measurement of the minimum deviation involves manipulation and rotation of both the telescope and the prism, so that the method, although accurate, is tedious.

An alternative method used by Bunsen and Kirchoff, is shown in Fig. VIII. 4. A scale photographed upon glass is placed in the focal plane of a lens. It is illuminated from behind, and by reflection from the last face of the prism, an image of the scale is superimposed on the spectrum. The prism is arranged to be in the position of minimum deviation for the yellow sodium line. The position of known lines can then be read off on the scale (the prism and telescope are now fixed) and a calibration curve drawn in the usual way.

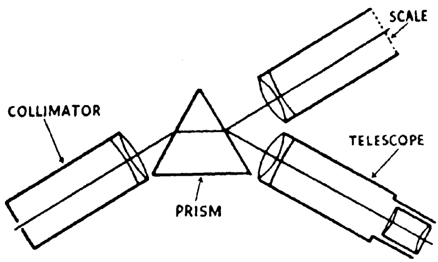


Fig. VIII. 4. Bunsen spectroscope.

It may also be used as a simple spectroscope, a photographic plate being fixed in the focal plane of the telescope objective. The method consists in obtaining upon the same plate photographs of the unknown spectrum and a standard spectrum, the unknown wavelengths are then obtained by interpolation between the wavelengths of the lines in the standard spectrum. The iron arc is generally used to provide the standard, because of the large number of sharp lines in its spectrum.

The Direct Vision Spectroscope (Fig. VIII. 5)

This is the simplest form of spectroscope. It consists of a tube containing a slit into which slides another tube containing an achromatic lens, a train of prisms, and a circular diaphragm. The instrument is

pointed directly towards the light source, and the spectrum observed by viewing through the diaphragm. (Here the spectrum is formed on the retina of the eye.) The train of prisms may consist, as shown, of five prisms, the second and fourth being of Flint glass and the others of Crown glass, or of three prisms, the centre one of dense Flint glass,

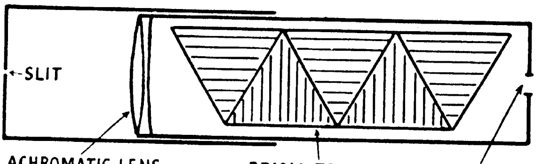


Fig. VIII. 5. Direct vision spectroscope.

the other two being of Crown glass. This combination allows the middle yellow ray to pass through without deviation, deviates the red to one side and the violet to the other. For quantitative work comparison with a photographic scale reflected from the last face of the prism train is used. The advantage of this instrument is that it is small, compact, fits into the pocket, and gives immediate and quick information. It is, however, not very accurate and is mainly used for preliminary qualitative work.

Constant Deviation Wavelength Spectrometer (Fig. VIII. 6)

The collimator and telescope are fixed at right angles to each other, and the only adjustment is the rotation of a large drum on which the wavelengths are marked directly. This drum forms the head of a fine tangent screw which rotates a table on which the constant deviation prism is mounted. The prism is made in one piece but can be regarded as built up of two 30° prisms (equivalent to a 60° prism) and a right-angled prism. As the prism rotates every ray in turn passes through the prisms at minimum deviation, and is deviated through 90°.

This type of fixed-arm spectrometer is very suitable for use as a *Monochromator*, i.e., an instrument for the production of light of one wavelength, since it is usually essential that there should be no alteration in the relative positions of the principal apparatus and the illuminator. Any fixed arm spectrometer can be used. It is only necessary to replace. the telescope eyepiece by a slit placed in the focus of the telescope lens.

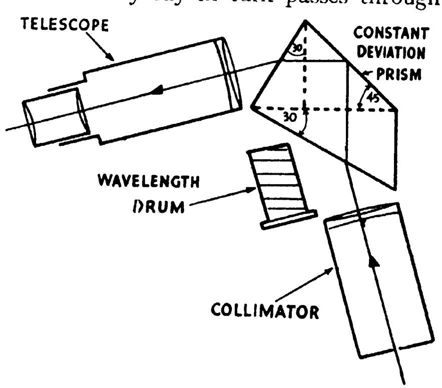


Fig. VIII. 6 Constant deviation wavelength spectrometer.

Ultra-Violet Spectrographs and Monochromators

Glass is opaque to most of the ultra-violet rays, i.e., those wavelengths shorter than the violet. Such rays produce no visual response in the eye. Thus only non-visual methods of detection and measurement are possible and these are generally photographic or photo-electric.

For the purpose of wavelength comparison, quartz spectrographs are used. The glass prism of Fig. VIII. 2 is replaced by a quartz prism, and the lenses are also of quartz. Owing, however, to the change in the focal length of the lenses with wavelength, the photographic plate is inclined to the axis of the instrument. For best definition the surfaces of the lenses are figured aspherically. A comparison standard spectrum is used in the usual way.

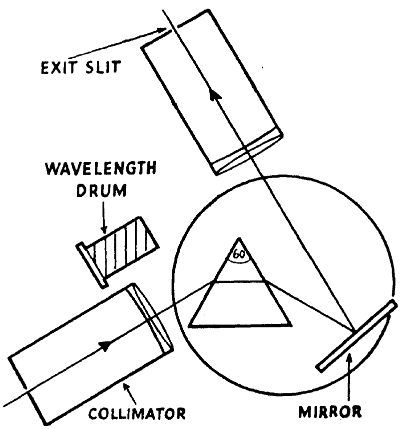


Fig. VIII. 7. Wadsworth constant deviation monochromator.

In the U.V. the constant deviation Monochromator uses a Wadsworth mounting to minimise absorption of U.V. radiation by the quartz. The optical arrangement is shown in Fig. VIII. 7. The plane mirror is front surface aluminised, as aluminium has a higher reflecting power in the ultra-violet, that of silver being low. Since the lenses are not achromatic, provision is made for adjusting their positions relative to the slits. The prism and mirror stand on one table, which is rotated by a fine steel screw, the wavelength being read off on a helical drum, each wavelength in turn passing through the prism at minimum deviation. For use as a spectrometer in the U.V., a fluorescent eyepiece replaces the exit slit.

Infra-red Spectrometer and Monochromator

The optical layout is similar to that of the U.V. instrument in that the Wadsworth mounting is used, but the collimator and telescope systems are replaced by stainless steel or aluminised concave mirrors. The type of prism material used, however, depends on the infra-red limit and dispersion required and may consist of fluorite, rocksalt, sylvine or potassium bromide.

The eye, photo-electric cells and photographic plates are all insensitive to the far infra-red rays. The method of detection consists of placing behind the exit slit some instrument which converts the radiation into heat and then measures the minute change of temperature produced. For most purposes a linear thermopile in conjunction with a sensitive short period galvanometer is used, together with, if necessary, some amplifying device.

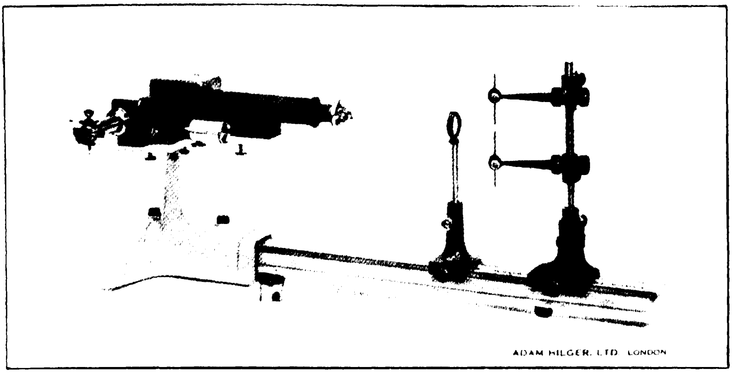


Fig. VIII. 8. Constant deviation spectrometer showing arc and condenser.

Other Types

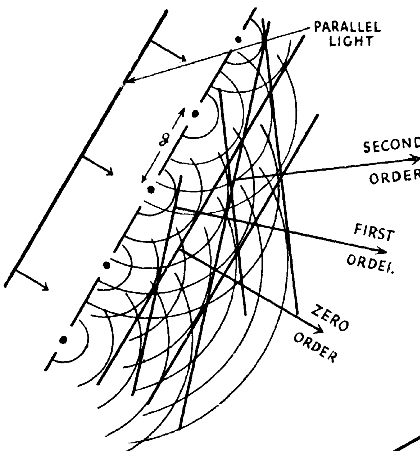
There are many modifications used for special purposes, such as the Spekker Steeloscope for the quantitative estimation of small impurities or alloying metals in steel, double monochromators, instruments with multiple prisms, and so on.

The Diffraction Grating

Apart from its importance as a means of identification of the substances concerned, the accurate measurement and distribution of the different wavelengths produced by a particular element or compound is very important from the purely scientific point of view, since it gives additional important information which helps to determine the structure of the atom. It was in fact one of the earliest triumphs of the Quantum Theory as applied by Bohr in 1913, that it brought order to the distribution of wavelengths in line spectra, using the conception of electrons rotating round a central nucleus. The instrument used most frequently for the accurate measurement and comparison of wavelengths is the Diffraction Grating.

The Transmission Grating

The simple transmission grating consists of a large number (usually about 14,500 to the inch) of equidistant transparent slits, separated by opaque portions. The width of each slit is of the order of a wavelength (λ) of light (about 5×10^{-5} cm.), while the distance between consecutive slits is of course 1/14,500 in. or about three wavelengths of light. As a consequence of the minute size of each slit, light that passes through it spreads out in all directions. If we consider this happening simultaneously at all the slits or apertures, when a plane wave from a collimator falls on it, then it is clear from the diagram (Fig. VIII. 9) that there is a direction, such that the light from successive apertures has travelled exactly one wavelength further than that of the preceding one. A second lens will therefore focus these waves in its focal plane,



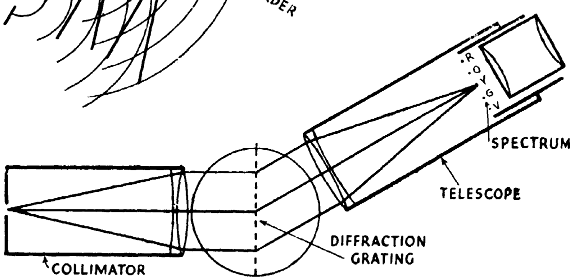


Fig. VIII. 9 (top). Action of a diffraction grating.
Fig. VIII. 10 (bottom). Simple transmission diffraction spectroscope.

thus forming a "diffracted" image of the slit of the collimator. It is clear that further diffracted images will be formed when the path difference is 2λ, 3λ, etc. In addition the central image will be formed at $\theta = o$ ($n = o$) where there is no path difference. From the diagram we can see that the grating condition is

$$g \sin \theta = n\lambda \quad . \text{ where } n \text{ is an integer.}$$

Thus every different wavelength in the original light produces an image of the collimator slit in different positions in the focal plane of the telescope lens. This of course constitutes a spectrum. It will be evident that for $n = 1$ (giving the first order spectrum) there are two spectra symmetrically spaced about the zero. $n = 2$ gives the second order spectra and so on. Usually the first and second order spectra are the only ones used (since the intensity of spectra of higher orders decreases rapidly.) Fig. VIII. 10 indicates also the simplest type of Diffraction Spectroscope. It is identical with Fig. VIII. 3 except that the prism is replaced by the grating. Clearly, by measuring the angle of diffraction on the divided circle, and knowing the grating space, the wavelength may be calculated.

The Concave Reflection Grating (Fig. VIII. 11)

Rowland, in 1882, succeeded in ruling very accurate equidistant lines of about 14,000 to the inch on concave metal surfaces by using a diamond

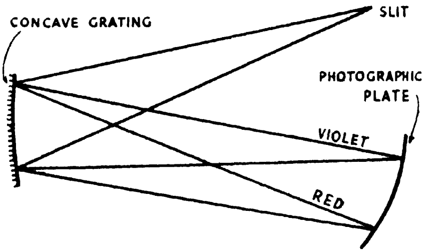


Fig. VIII. 11. Concave reflection diffraction grating.

point moved by a dividing engine controlled by an extremely accurate screw. The spectra were now formed by reflection instead of transmission, and owing to the concave surface, were self-focusing, thus eliminating use of lenses. The light is incident direct on to the grating via a slit, and the various orders of spectra are produced automatically in focus on a calculated curve, on which the photographic plate or film is placed. In this way there is no limitation of wavelength range, from the long infra-red to the short ultra-violet.

The Vacuum Spectrograph

Since the atmosphere absorbs the very short U.V. radiation both prism and grating spectrographs for work in the extreme U.V. are enclosed in evacuated containers.

Direct Vision Grating Spectroscope

The principle of the method is shown in Fig. VIII. 12. White light entering normally on one surface of a prism, enters undeviated, then falls on the grating and is diffracted out in all directions. With a grating of 14,000 lines to the inch, and a prism angle of about 33°, the middle of the visible spectrum is undeviated. This gives a much wider and better resolved spectrum than the direct vision prism spectroscope, but it is not as bright. It can, however, be used for more accurate quantitative work than is possible with the corresponding prism instrument, provided the light is sufficiently intense.

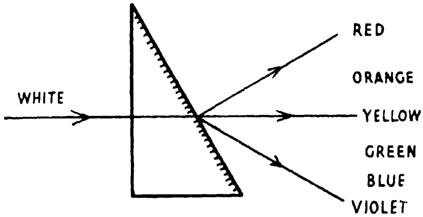


Fig. VIII. 12. Direct vision grating spectroscope.

The Echelon Grating is a very high resolving power instrument used only for the examination of the fine structure of spectral lines.

X-Ray Spectroscope

The range of wavelengths comprised by X-rays varies from about 4×10^{-7} cm. to less than 3×10^{-9} cm. (The shorter the wavelength, the harder or more penetrating the X-ray.) The structure of matter is too coarse to provide regular reflection or refraction for these minute waves, so that no systems of lenses or prisms are possible.

In fact, the individual atom of matter itself acts as a scattering centre and diffracts in all directions an X-ray wave reaching it. This idea was used first by von Laue in 1912, who showed that a natural crystal may be looked upon as a three-dimensional diffraction grating so far as its effects on X-rays are concerned. The method was improved soon after by W. L. Bragg, who showed that X-rays are regularly reflected by cleavage planes in crystals. Such planes are rich in atoms which are arranged in a regular way. Further, these cleavage planes are equidistant from one another. Fig. VIII. 13 illustrates the way in which X-ray reflection occurs. The intensity of reflection at any one cleavage plane, however, is extremely minute, and in order that the reflections from the hundreds of such planes in the crystal should add up the path difference between reflection from successive planes must be a whole number of wavelengths. This means that only if $2d \sin \theta = n\lambda$ will "reflection" take place, where d = distance between cleavage planes and θ = glancing angle of reflection. This relation is known as Bragg's Law.

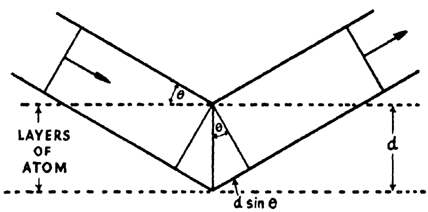


Fig. VIII. 13. Reflection of X-rays by cleavage planes of a crystal.

For a Rock Salt crystal (a simple cube) the value of d is known from other considerations, so that by measuring θ the wavelength of X-rays may be calculated.

Bragg X-Ray Spectrometer (Fig. VIII. 14)

This was the first instrument by which an accurate value of the wavelength of X-rays was obtained. A fine beam of X-rays is directed on to the crystal by two fine slits in the lead screens (a small thickness of lead being opaque to all but the hardest X-rays). On reflection they pass through a third slit, the purpose of which is to cut out stray scattered X-rays, and then enter the ionization chamber through a thin aluminium window. The aluminium is transparent to X-rays, and keeps the chamber airtight. The ionization chamber is an arrangement which detects and also if necessary measures the relative intensity of the reflected X-ray beams. The crystal and the chamber are rotated simultaneously, the latter being always rotated through twice the angle of the former. This procedure is repeated for the different cleavage planes

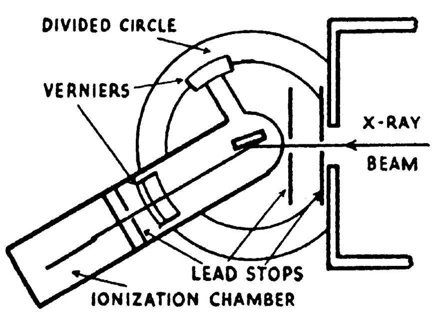


Fig. VIII. 14. X-ray spectrometer.

of the crystal. In this way an ionization curve is obtained, from which the "reflection" angles are found, so that the wavelength of the X-rays may be calculated.

X-RAY SPECTROGRAPH

The use of the ionization chamber (except for some special purposes) has been largely superseded by photographic film which makes for much greater accuracy and simplicity. This is usually bent round into an arc concentric with the axis carrying the crystal, which is slowly rotated throughout the exposure. When a particular reflecting plane in the crystal is at the correct angle, a reflected ray is momentarily produced which records itself on the photographic film. The intensity of the "lines" so produced is increased by rotating the crystal a sufficient number of times. The spectrum appears symmetrically on either side of the central bright band, this band being due to radiation which has passed straight through the crystal. The procedure is repeated for the different planes.

It is clear that the Bragg Law may be used in two ways. Using a known crystal the wavelengths contained in a source of X-rays may be determined, or using one or more known wavelengths, the structure of an unknown crystal may be found. An instrument specially adapted for the latter purpose is often called an *X-ray Crystallograph.*

The X-ray Powder Spectrograph

Relatively few substances give large single crystals, so that the Bragg method is of limited application.

The powder method is of much wider scope. It uses the material in a very finely-divided state enclosed in a thin-walled capsule. The specimen consists therefore of a very large number of minute crystals, orientated entirely at random. Using an X-ray beam consisting of one wavelength only, and allowing it to fall on the powder, there will be reflections taking place simultaneously from those crystals of which the reflecting planes fulfil the Bragg condition. Thus a single photograph gives a complete picture of the crystal structure. Since, however, only a few of the crystal grains are effective for a particular direction, the reflected beams are weak, and therefore an X-ray beam of high intensity must be used together with long exposures.

In the soft X-ray region (greater than 2×10^{-8} cm.) the absorption due to air becomes very strong, so that the spectrograph must be placed in an evacuated chamber. In the case of hard X-rays (less than 7×10^{-9} cm.) the glancing angle becomes very small, and special modifications have to be adopted for accurate measurement.

The Grating X-ray Spectrograph

In 1922 it was shown that X-rays could be regularly reflected from the polished plane surface of a piece of glass, provided that an extremely small glancing angle of not more than 10 minutes of arc was used. This is analogous to ordinary optical reflection and not to X-ray crystal reflection which is a body effect and requires penetration of the X-rays through hundreds of planes. The reason lies in the fact that the refractive index for X-rays passing from air to the glass is just less than unity ($1 - 8.12 \times 10^{-6}$ for wavelength 1.54×10^{-8} cm.).

As a result X-rays passing from air to glass are entering an optically less dense medium, so that for angles of the order of 10 minutes of arc or less total reflection takes place. If lines are ruled on the surface of the glass (they vary from 200 to 1,100 lines per mm.) then in addition to the reflected beam, diffracted beams are also produced, following the same laws as optical diffraction gratings. The angles of diffraction, though small, can be measured very accurately. It provides an absolute method of measuring X-ray wavelengths, particularly in the long wave X-ray regions where crystals with suitable cleavage plane spacings do not exist. The grating space of the diffraction gratings are measured by using known optical wavelengths.

For special purposes the concave grating has also been used owing to its focusing properties.

Practical Applications

A short indication of some of the everyday applications of X-ray spectroscopy and crystallography may not be out of place. These include first the determination of the crystal structure of materials of such diverse kinds as metals, alloys, geological and mineralogical crystals, including precious stones, chemical crystals, organic materials of all kinds, including wool, hair, fibres, rubber, celluloid and plastics of all kinds. Secondly, the industrial application of the identification of unknown samples by comparison with previously determined structures, and in the field of metallurgy, apart from structure determinations, the determination of the effects of heat and mechanical treatment on metallic alloys. It has also been extended to the determination of the structure of some organic molecules.

Finally, the importance of X-ray wavelength measurements from the scientific point of view cannot be over-estimated. It led Moseley in 1912 (he was killed in the World War, 1914-1918) to the idea of the atomic number instead of the atomic weight as being the most important property of an element, the result of which produced far-reaching and fundamental changes in physical and chemical ideas.

MASS SPECTROGRAPH AND MASS SPECTROMETER

The phenomenon of radio-activity had by 1910 suggested the existence of *Isotopes*, that is elements which have practically identical chemical and spectroscopic properties, but different atomic weights and thus different densities. They cannot be separated by chemical methods. The first tentative evidence that non-radioactive elements may also consist of isotopes was obtained by Sir J. J. Thomson in 1912. His experiments led him to the belief that neon of atomic weight 20.2 consisted of two isotopes of masses 20 and 22, a result which was only definitely proved when the first mass-spectrograph was constructed by Aston in 1919. He followed this up by proving the existence of isotopes in many other non-radioactive substances.

Mass Spectrograph

This is an instrument which will detect, sort out and measure the relative masses of extremely minute quantities of atoms, and molecules, far beyond the range of chemical methods. It gives direct information

as to the *individual* masses of the constituent atoms of elements and molecules of compounds, and not as in chemistry to the mean mass of an immense aggregate. It does this by producing a focused mass spectrum of lines on a photographic plate, each line representing a different atom or molecule. By measurement of the relative positions of these lines their masses can be compared to an accuracy which in the latest instrument is claimed to be one part in a million. It is therefore vital to the discovery and investigation of isotopes.

Mass Spectrometer

This is specially designed to detect and measure the relative abundance of the isotopes of a particular substance, by bringing a focused beam of mass rays of each isotope in turn to a fixed slit, and measuring the intensity electrically, the relative abundances being proportional to the intensities.

At the present time many different types of either instrument are in use.

One essential factor common to all is some device for producing positive ions (or positive rays) of the atom or molecule in question. Such rays were discovered by Goldstein in 1886 in electrical discharges in gases at low pressure. They move from the anode to the cathode. By the provision of an aperture in the cathode, they pass through and may be investigated. In this way Wien in 1898 showed that they could be deflected by a magnetic field, and subsequently Sir J. J. Thomson showed that they carry a charge of positive electricity. These positive rays are now identified as atoms or molecules which have lost one or more electrons by ionization at low pressure in a strong electric field, and so carry a positive charge. As a result of falling through the high potential they have sufficient energy to make their presence detectable and their mass measurable.

In practice the methods of producing particular positive rays vary according to whether the substance is gaseous, liquid, or solid with a high or low boiling point. In a form other than gaseous the method in principle consists of vaporising the substance by direct or indirect heat, and then ionizing and accelerating the resultant atoms by a suitable electric field. They are then analysed by the mass spectrograph.

Aston's Mass Spectrograph

The rays generated in the discharge tube used by Aston are heterogeneous. That is they contain particles of different mass having different velocities and different energies. The essential feature of this mass spectroscope is an arrangement of electric and magnetic fields such that all rays of constant e/m are brought to a focus at the same point on a photographic plate. Fig. VIII. 15 illustrates the principle of this method. The rays from the discharge tubes are collimated by two fine slits, and are then deviated by an electric field. This spreads out the beam, the rays with large energy being deviated least, and vice versa. A group of these rays is selected by the diaphragm and then deviated in the opposite sense by a magnetic field perpendicular to the plane of the paper. They emerge from the magnetic field in such a way that they converge on to a photographic plate arranged as shown,

those particles with small e/m (large mass) coming to a focus in the region of F, whilst those with large e/m (small mass) come to a focus in the region of G.

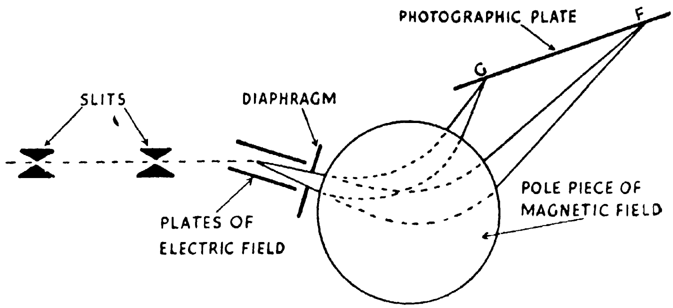


Fig. VIII. 15. Aston's mass spectrograph.
Particles of small $\frac{e}{m}$ at F. Those of large $\frac{e}{m}$ at G.
e = electronic charge. m = atomic mass.

Particles with the same mass may be singly charged, or multiply charged. That is they may be ionized to such a degree that they lose a number of electrons, so that a particle of given mass may have a number of values of e/m. They will come to a focus at different points on the photographic plate.

The latest (1939) development of the Aston Mass Spectrograph, although using the same method, contains many refinements and modifications, giving it considerably greater power and sensitivity.

Double Focusing Instruments

Aston's use of fine slits to produce a fine parallel beam, means that a large proportion of the initial mass rays are lost. As a consequence long exposures are necessary, and rare isotopes will produce too faint a trace to be observed. The principle of double focusing is applied to those methods by which collimation is unnecessary. A beam of mass rays diverging from a slit is deflected and focused by a combination of electric and magnetic fields in such a way as to converge the beam and produce the equivalent of an "image" of the original slit. It is the exact analogy of an optical lens system collecting light diverging from a slit and converging it to an image slit. It is clear that such an arrangement will produce a much more intense image than Aston's arrangement, with a consequent reduction in exposure time.

Bainbridge and Jordan's Double Focusing Mass Spectrograph (Fig. VIII. 16)

A beam of mass rays generated in the discharge tube passes through a narrow slit (S_1) and a wider slit (S_2) which defines the limit of divergence of the beam. It is then deflected by a radial electric field through

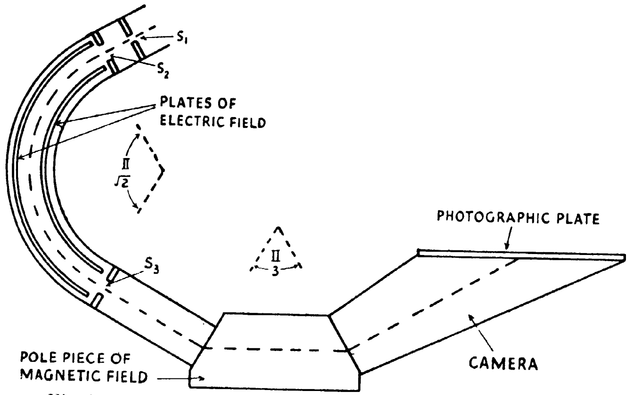


Fig. VIII. 16. Bainbridge and Jordan mass spectrograph.

an angle of $\pi/\sqrt{2}$ radians, and after further control by a variable slit (S_3) is next deflected by a concentrated specially designed magnetic field through an angle of $\pi/3$ radians and comes to a focus on the photographic plate as shown. The focusing is extremely sharp over the length of a 140 mm. spectrum, and constitutes one of the most powerful instruments in use.

Nier's Mass Spectrometer (Fig. VIII. 17)

This is based on an earlier instrument designed by Dempster in 1918 in which an ion beam of constant energy is deflected and focused by a uniform magnetic field only. It is not a double focusing instrument.

The rays are formed by direct ionization of the vapour of the element concerned, or one of its compounds, by means of a tungsten filament. As they pass through the entrance slits, they are accelerated by suitable

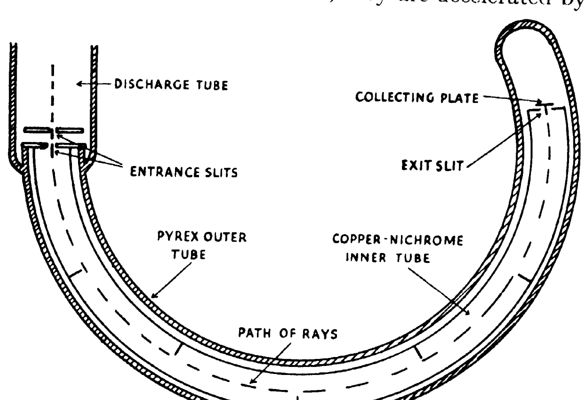


Fig. VIII. 17. Nier mass spectrometer.

voltages and are then bent through a semi-circle by a large electro-magnet, coming to a focus on the exit slit, whence they are collected on a plate situated just behind the slit and measured by a valve amplifying device whose sensitivity can be increased almost without limit, so that abundances as low as 1 in 100,000 can be detected.

As the accelerating field is altered particles of different e/m will in turn be focused on the exit slit. The experimental procedure consists in plotting the ionic current against accelerating potential. The peaks on the curve correspond to definite values of e/m and their heights to the relative quantities of the particles present in the beam.

The special feature of the Nier instrument is that the ion path is enclosed in a nichrome and copper tube which in turn is enclosed by a sealed pyrex glass container. This enables very low pressures to be attained, and thereby, among other advantages, secures the complete exclusion of contamination.

Other modern instruments of high power which can only be mentioned are the double focusing instrument of Mattauch which gives perfect focusing over the whole mass range on a plate of 300 mm., and the latest and most powerful instrument of all designed by Jordan, which combines double focusing with velocity selection.

These instruments have been built not only for examining the presence and abundance of various isotopes, but also for finding out exactly by how much the isotopic weights differ from whole numbers. The earlier instruments had already shown that almost all the isotopes differed very slightly from whole numbers, and the accurate value of this divergence is of great theoretical importance. Among other things, for example, it verifies to a high degree of accuracy Einstein's theory of the quantitative equivalence of matter and energy, a result arising from the theory of relativity, and it provides a very exacting test of theories as to the constitution of the nucleus.

Industrial Application

Within recent years an instrument of the Nier type, although of a higher power, is playing a very important part in the petroleum industry. It is found that each hydrocarbon, such as methane, ethane, etc., gives its own particular sequence of intensities of the various carbon groups known as its "cracking pattern," which serves to identify both qualitatively and quantitatively the particular hydrocarbon present. From previous empirical knowledge it is possible to deduce the actual composition of a complex mixture of hydrocarbons with an accuracy of better than $\pm$ 5% of each of the various constituents. Furthermore, this can be done in a very short time, and requires only a minute sample, which represents a great improvement all round on standard chemical methods.

Both the mass spectrometer and mass spectrograph have been used on a small scale for other chemical problems, and there seems no doubt that in time they will find increasing application in the chemical and allied industries.

CHAPTER IX

THE TELESCOPE

Telescopes can be divided into two classes, *refractors* in which the primary image is formed by means of a system of lenses, and *reflectors* in which it is formed by a system of mirrors; with the exception of the *Galilean* form of refractor the image is *real* and can be caused to fall on a photographic plate, the slit of a spectroscope, etc., and can be magnified for visual inspection by means of a simple or a compound microscope.

REFRACTING TELESCOPES

The Astronomical Telescope (Fig. IX. 1) consists of an *object-glass*, usually of two components (a biconvex crown lens and a plano-concave

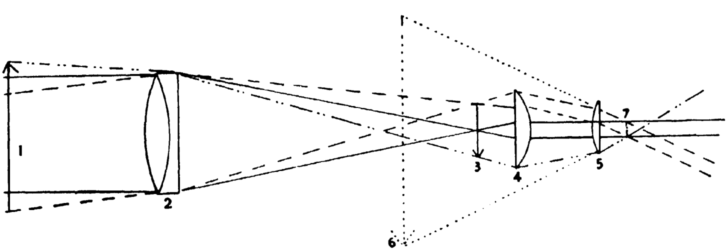


Fig. IX. 1. Astronomical telescope. Key: 1, Distant object; 2, Object-glass; 3, Image at focus of object-glass, real and inverted; 4 and 5, lenses of eyepiece; 6, Image as seen by eye, virtual and inverted; 7, Ramsden disc. (The eyepiece is of the Ramsden form.)

flint) to eliminate chromatic aberration, and of fairly long focal ratio (*f*. 12 upwards) to eliminate spherical aberration: this forms a real and inverted image of a celestial object which can be allowed to fall on a photographic plate as in *astrographic* telescopes, or on the slit of a spectroscope, or on a photo-electric cell, or can be examined visually by means of an *eye-piece* or *ocular* which is effectively a simple microscope whatever its construction may be; the image as seen through the ocular remains inverted, but this is of no significance in astronomical work and the simplicity of the construction leads to the minimum number of air-glass surfaces with their inevitable loss of light by reflection and the impairment of definition to which a multiplication of surfaces (which in the very nature of things can be no more than close approximations to a perfect optical surface) would give rise. The ocular most commonly used is of the *Huyghenian* construction customarily used for microscopes, but the *Ramsden* form, or the more complex *monocentrics*, *aplanats*, etc., all of which have their focal plane in front of the lens system and so can be used with graticules, etc., in focus with the image, are more convenient and optically preferable. (See Chapter I on Lenses.)

The Terrestrial Telescope (Fig. IX. 2) or spy-glass differs from the astronomical telescope only in its eyepiece, which is designed to compensate the inversion of the image at the primary focus so as to present

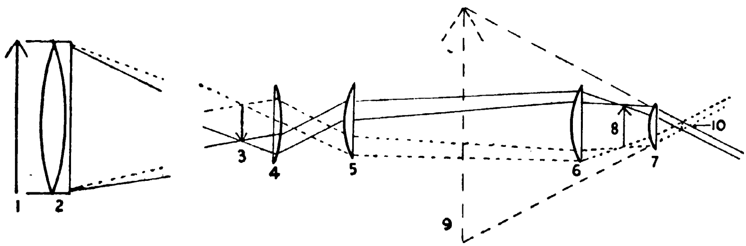


Fig. IX. 2. Terrestrial telescope. 1, Distant object ; 2, Object-glass ; 3, Image at focus of object-glass, real and inverted ; 4 and 5, Lenses of erector ; 6 and 7, Lenses of eyepiece ; 8, Secondary image, real and erect ; 9, Image as seen by eye, virtual and erect ; 10, Ramsden disc. (The eyepiece is of the Huyghenian form.)

to the eye an *erect* image which is obviously essential for terrestrial observation. The arrangement most commonly used is an *erector* consisting of a pair of lenses which project an erect and somewhat enlarged image of that in the focal plane of the object-glass into the focal plane

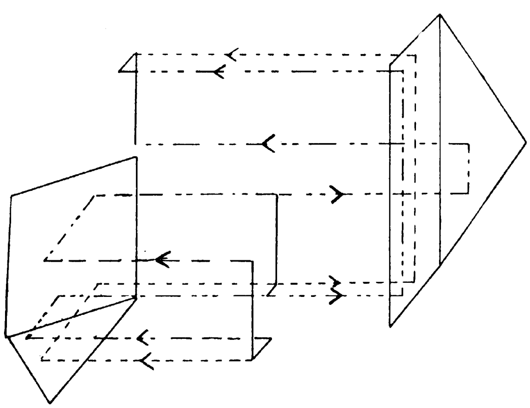


Fig. IX. 3. Path of rays through Porro prisms.

of the eye-piece (it may be noted that the combination of erector and eye-piece is essentially a low-powered compound microscope and can be used as such, and conversely that a low-powered microscope can be used as a compound eye-piece for a telescope) ; the erector and eye-piece are commonly fixed at the opposite ends of a tube, but occasionally, in the so-called *pancratic* (variable magnification) eye-pieces, their separations can be altered to give a variety of magnifications.

The Prismatic Telescope (Fig. IX. 3) usually encountered in the form of prismatic binoculars, is again an astronomical telescope modified to give an erect image. While other arrangements exist, the usual construction is due to Porro ; in this the rays from the object-glass undergo two successive internal reflections at the cathetus-faces to each of two right-angled prisms set with their planes of reflection at right angles to each other : an examination of the illustration will make their mode of action far clearer than can any verbal description—it may be noted that the cathetus-faces can be replaced by reflecting surfaces, and that the prisms can themselves be divided into pairs.

The Galilean Telescope (Fig. IX. 4) is usually met with in the form of *opera glasses* and *night glasses* where a low magnification and small

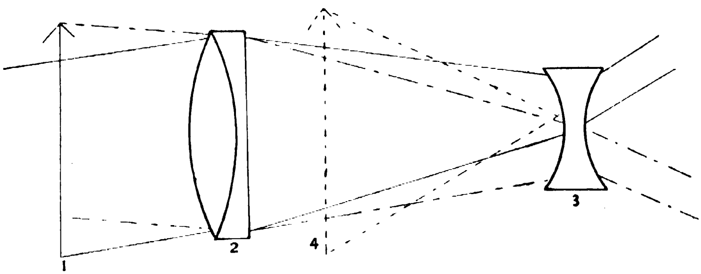


Fig. IX. 4. Galilean telescope. 1, Distant object ; 2, Object-glass ; 3, Biconcave eyepiece ; 4, Image, virtual and erect.

field of view are of less importance than light weight, compactness, and low loss of light : unlike the types already described, no real image is formed. It consists of an object-glass, and a bi-concave eye-lens set well within the focus of the former so that the converging rays are made to diverge as if they originated at an object set at the nearest distance of distinct vision. The image is erect and the system behaves well enough for the uses to which it is commonly put even if the lenses are simple, while if more perfect correction is needed both the object-glass and eye-lens can be cemented achromatic combinations.

The Periscope and such instruments as the *Cystoscope*, *Introscope*, etc., are of the same fundamental construction. Fig. IX. 5 is included here as being essentially a specialised form of telescope. Two basic forms of construction are employed. If a short and fairly large instrument is permissible, a modification of the prismatic telescope is available (Fig. IX. 5a) ; here a totally-reflecting prism is placed at the head of a vertical tube in front of the object-glass, while at the base of the tube a second totally-reflecting prism (it will be seen that these correspond to the first double-reflecting prism in the Porro system) and a double-reflecting prism return the light to a horizontal eye-piece. Generally, however, the instrument must be relatively long and slender (as in the submarine periscope) and a different construction must be followed (Fig. IX. 5b).

Omitting the prisms at the top and bottom of the tube, which serve only to reflect the light downward and then horizontally, the construction

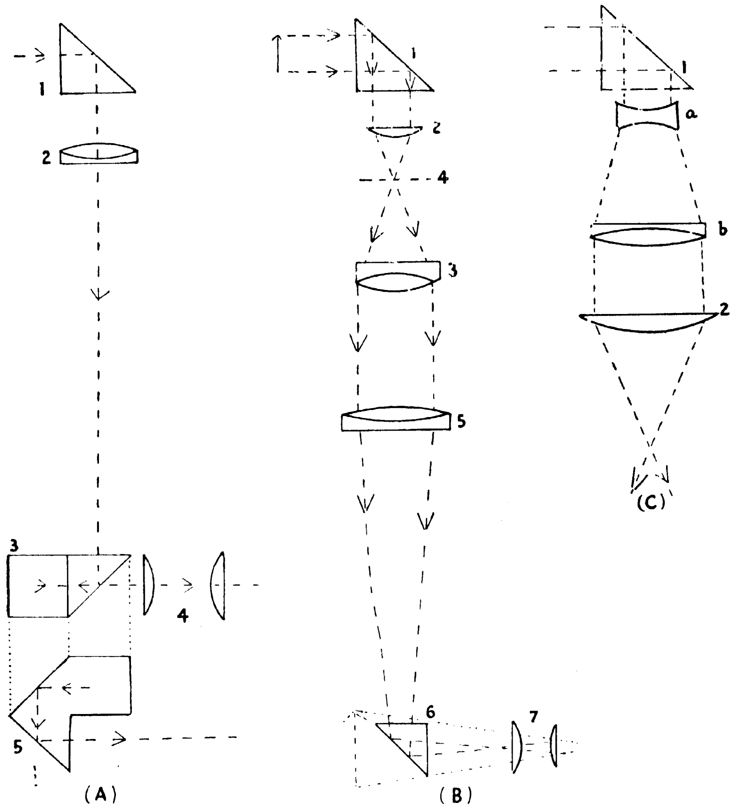


Fig. IX. 5. Periscopes. (A) Periscopic telescope: 1, Upper prism; 2, Object-glass; 3, Lower prism; 4, Eyepiece; 5, Plan of lower prism. (B) Submarine periscope: 1, Upper prism; 2, 'Eyepiece' of first telescope; 3, Object-glass of first telescope; 4, Common focal plane of 2 and 3; 5, Object-glass of second telescope; 6, Lower prism; 7, Eyepiece. (C) Upper part of B for large field. 1 and 2 as in B. *a* eyepiece and *b* object-glass of reversed Galilean telescope.

is essentially two astronomical telescopes, the first of lower power than the second, placed with their *object-glasses* facing each other. The eye-lens of the first telescope produces a greatly-reduced image of the object under view in the focal plane of the first object-glass, through which the light is passed as a parallel beam to the object-glass of the second telescope: this forms an image in its own focal plane which is viewed through the eye-piece by means of the lower prism. The final magnification is in proportion to the powers of the two telescopes (e.g. if the first is $\times 12$ when used as a telescope in the normal way, it will *reduce* the image to 1/12 when used 'in reverse,' while the second telescope being, say $\times 24$, will magnify this reduced image $\times 2$ ($1/12 \times 24$)). The field of view

is rather small, and when a field corresponding to that seen by the naked eye is required, an additional lens system is necessary ; this very frequently consists of a reversed Galilean telescope set in front of the 'eye-piece' of the first telescope (Fig. IX. 5c), the concave and convex lenses being of such a distance apart as to pass a beam of parallel rays on to the "eye-piece," and being so mounted as to be capable of insertion into, or removal from, the beam of light from the upper prism. It must be borne in mind that this simple construction has frequently to be complicated by the introduction of additional unit-magnifying telescopes in order to pass the maximum amount of light down a long and very narrow tube, and that the prism at the head of the tube is frequently somewhat complex both in structure and mounting.

The object-glass of a telescope is fixed at one end of a metal tube, blackened internally and also fitted with stops to eliminate stray light from the wall since even optical black paint is slightly reflective at extreme incidence ; at the opposite end of the tube is a second one moving in and out either by simple friction or mechanically, at the end of which is the eyepiece. This construction is invariably employed for astronomical instruments and for terrestrial instruments where great portability is not requisite ; where portability is essential the main tube is itself divided into sections sliding one within the other. Prismatic telescopes are mounted in cases enclosing the prisms, and focusing is effected almost invariably by movement of the eye-piece, though occasionally by movement of one of the prisms.

REFLECTING TELESCOPES

The Reflecting Telescope may take one of four forms ; the most common is the *Newtonian* ; the *Gregorian*, which affords an erect image,

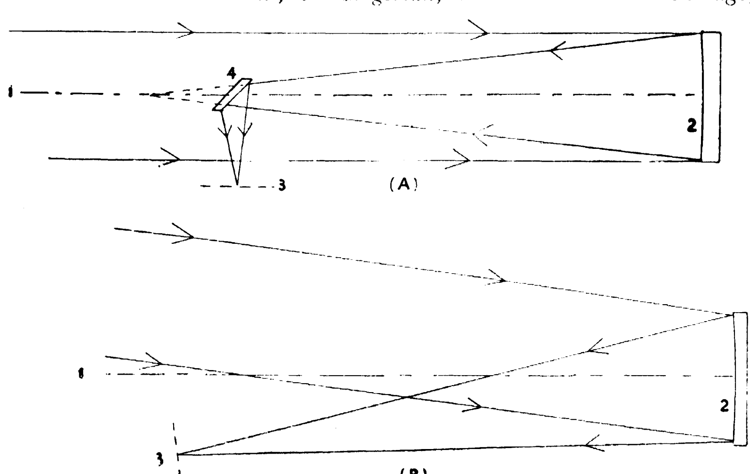


Fig. IX. 6. (A) Newtonian reflector. (B) Herschellian reflector. 1, axis of mirror ; 2, Concave paraboloid mirror ; 3, Focal plane of 2 ; 4, Diagonal mirror

was formerly common and may be encountered as an antique; the *Cassegrainian* has become more common of late years; and the *Herschellian*, which is now rarely found except in the form of fixed instruments of high focal ratio. In all, the image is produced by a concave paraboloidal mirror, silvered or aluminised on its front reflecting surface, and the rays of light converge to a focus in front of the mirror, and, save in the Herschellian form, in the axis of the telescope. In the Newtonian form (Fig. IX. 6 (a)) the convergent rays fall on a plane reflector (or in small instruments a right-angled total-reflection prism) set within the focus, so that the image is formed at a convenient place to the side of the tube within which the mirror is mounted, excepting occasionally in photographic work when a comparatively small plate is set in the axis at the focal plane. In the Herschellian (Fig. IX. 6 (b)) the second reflection is avoided by setting the mirror a trifle askew, but except with mirrors of great focal ratio this introduces serious aberrations and in consequence the construction is rarely employed to-day (when it was first introduced by Sir Wm. Herschell at the end of the eighteenth century the only reflecting surfaces available were of "speculum metal," the reflecting power of which is somewhat low even when newly polished, and the loss of light from a second surface was felt to be more serious than the aberrations introduced by the use of only one).

In both the *Gregorian* and *Cassegrainian* forms (Fig. IX. 7A and 7B) the primary image is enlarged by a secondary mirror set in the axis of

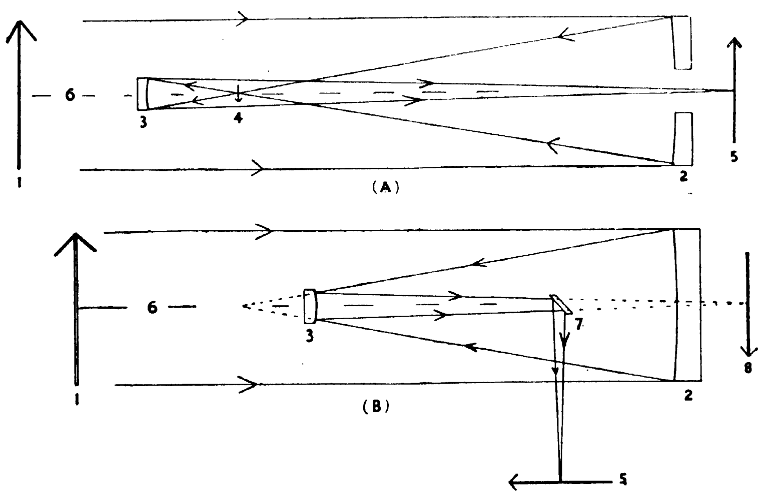


Fig. IX. 7. (A) Gregorian reflector. (B) Cassegrain reflector (as used with unperforated primary mirror). 1, Distant object; 2, Primary mirror; 3, Secondary mirror. 4, Image in focal plane of primary mirror, real and inverted; 5, Image in focal plane of secondary mirror, real and erect in Gregorian, real and inverted in Cassegrain; 6, Axis of primary mirror; 7, Diagonal flat mirror in Cassegrain when used with unperforated primary; 8, Image in focal plane of secondary mirror when primary is perforated, real and inverted.

the primary. In the former case the secondary is a *concave ellipsoid* of such curvature as to have its one focus coincident with the focus of the primary while the second focus, at which the final image is produced, lies at a convenient distance behind the primary mirror which is pierced in its centre to permit passage of the light rays ; or, to avoid piercing the primary, a flat or prism may be set in front of it to reflect the rays to the side of the tube : the construction gives a rather small field and the concave ellipsoid is rather difficult to figure, while the position of the secondary mirror *beyond* the focus of the primary makes such an instrument rather cumbersome. In the case of the *Cassegrainian* the secondary mirror is a *convex hyperboloid*, set within the focus of the primary, the image being formed at any convenient distance behind the primary or to one side as in the previous construction : like the Gregorian the field is small, but the secondary is somewhat easier to figure, while its position within the focus makes for a compact instrument ; further it is easy to attain a very great equivalent focal length, which is occasionally requisite as when spectroscopes with long-focus collimators are in use. A considerable number of the larger astronomical reflectors are provided with several interchangeable Cassegrainian secondaries for use in appropriate circumstances.

Mention should be made of various highly-specialised forms of reflecting telescopes such as the Schmidt, Ritchey-Chrêtian, etc., which have been designed for photographic work ; in most of these the spherical and other aberrations of a concave spherical mirror of short focal length are corrected by means of a figured plate of glass, giving a wide field of view and a very low focal ratio.

Newtonian reflectors form the vast majority of the telescopes employed by both professional and amateur observers as they are devoid of chromatic aberration (as are the other reflectors) and can be constructed with focal ratios as low as *f*.6, thus giving a conveniently-sized instrument. In addition their construction does not demand optically perfect glass, which cannot be produced beyond a certain size—the inability to produce *large* pieces of glass of suitable quality, together with the great loss of light through absorption in the lenses, puts an upper limit to the size of *refracting* telescope, whereas it is mainly cost rather than technical obstacles that will limit the upper size of reflectors. Except in the case of small instruments, reflectors are invariably mounted in skeleton tubes which serve to keep the components in correct position and to connect them to the mounting ; this form of ' tube ' greatly reduces disturbances caused by air currents which are inevitably present in a tube which must be open at its upper end.

Mountings of Telescopes

Except in the case of binoculars and of small terrestrial telescopes, some form of stand is essential if the instrument is to be steady enough for comfortable observation. For terrestrial telescopes this can take the form of a vertical axis at the head of a tripod or column, allowing of movement in azimuth, while a cradle at the head of this axis carries the telescope by means of trunnions, so allowing of movement in altitude. Properly constructed, with the cradle given an overhang so that the

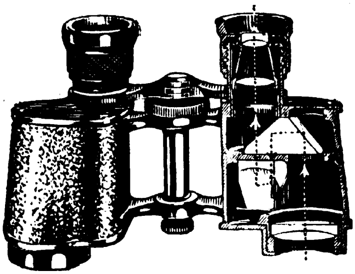


Fig. IX. 8. Section through a modern prismatic binocular.

telescope can be directed vertically upwards, and preferably fitted with slow-motion devices to both vertical and horizontal axes, such a stand serves for small refractors and medium reflectors when put to astronomical work ; but in so far as *two* motions are needed to follow a celestial object in this case, this *Altazimuth* mounting is not so convenient a mounting as the *equatorial*, and is quite unsuited for large instruments of either type.

Equatorial Mounting. It is obvious that if the vertical axis of the stand mentioned in the last paragraph is inclined until it is parallel to the earth's axis of rotation, a single movement will suffice to follow a heavenly body once it has been brought into the field of view, and this may be applied by means of clockwork of some sort. The telescope is connected to this axis of rotation—the *polar axis*—by some form of cross axis—the *declination axis,* so-called because it allows the instrument to be set in declination.

Equatorial mounts may take several forms. In the open fork type the polar axis carries at its upper end a cradle, in which the telescope itself is swung on trunnions which constitute the declination axis ; this form is available for reflectors only. The ' English ' mounting, in which the polar axis is supported both above and below the telescope, is found in two forms ; in one the central part of the axis is open, and the telescope swings in trunnions set in the two cheeks, while in the other the axis is complete and the telescope is set at one end of a declination axis passing through the polar axis and carrying a counterpoise at its outer end—after being disused almost completely for many years this form, which can be used equally for reflectors or refractors, has again come into popularity. The ' German ' form of mounting, still that most generally employed, has the declination axis set at the head of the polar axis, the telescope being at one end and a counterpoise at the other ; equally useful for either type of instrument, its main advantage over the preceding type is its single pillar and somewhat more compact form. Other forms of equatorial, in which the tube of the telescope itself forms the polar axis, have been made, but are few in number.

Occasionally—and particularly in certain branches of solar physics—it is desirable to use a refractor of considerable focal length ; in these cases it is usually most convenient to mount the telescope itself in a fixed (generally horizontal) position and to direct the light into it by a system of movable mirrors. The preferable arrangement of mirrors is the Coelostat, in which there is no rotation of the apparent field of view ; in this a plane mirror, with its reflecting surface parallel to the earth's axis, is mounted on a polar axis which can be moved along rails in the meridian so that light can be reflected to a second mirror mounted on vertical and horizontal axes in the optical axis of the telescope, the first mirror being rotated by means of clockwork. A second form, which

suffers from the disadvantage that the apparent field of view undergoes a slow rotation, but which has a much wider range of view in declination, consists of a plane mirror at one end of a polar axis, the light being reflected to a second mirror at the intersection of the polar axis and the optical axis of the telescope. It may be mentioned that while these instruments are usually employed with refractors, occasionally Herschellian reflectors of long focus, and in a few cases Cassegrainians, have to be used.

Transit or *Meridian Circles*, *Altazimuth Circles* and *Prime Vertical Transits*, together with zenith telescopes and certain other less common forms are employed in the astronomy of position for determining the positions of celestial objects. The first named is essentially a refractor constrained to move very exactly in the plane of the meridian; by timing the passage of a star over thin wires at its primary focus (or by equivalent means) the meridional passage of a star can be observed, while accurate circles allow of its distance from the celestial pole being determined. Altazimuth circles are essentially altazimuths of very rigid construction provided with circles by which the position of a celestial body can be determined out of the meridian, while the prime vertical transit is a transit mounted so as to move at right-angles to the meridian. The zenith telescope is employed mainly in the investigation of the variation of the latitude.

Some Theoretical Considerations

It is out of the question to deal with either the physical or geometrical optics of the telescope in the space available, but certain matters which have a bearing on the use of the instrument must be mentioned.

By reason of the fundamental nature of light, the image of a point-source (or of an extended object at such a distance as virtually to be a point) is not a point but a minute disc (*spurious disc*) surrounded by a system of concentric circles; the diameter of this disc is constant for a given aperture of lens but varies inversely with variation of lens diameter: it follows that there is a limit below which two adjacent points cannot be distinguished as separate entities since their spurious discs overlap too greatly (roughly this minimum separation, in seconds of arc, is given by dividing the diameter of the lens or mirror, expressed in inches, by 4.5—thus a telescope of 4.5 inches clear aperture will just separate two stars 1 second apart). This same phenomenon sets an upper limit to the *effective* magnification that can be employed, since no greater power is required, generally, than will serve to separate clearly the spurious

REFRACTOR WITH RAMSDEN EYEPIECE

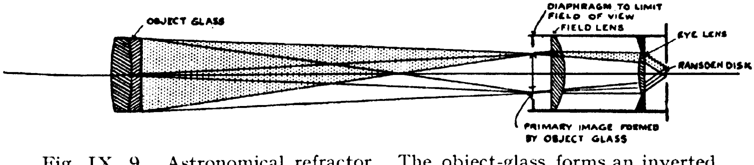


Fig. IX. 9. Astronomical refractor. The object-glass forms an inverted and real image in the focal plane of the eyepiece; this image, magnified by the eyepiece, is virtual and inverted.

discs of two points at the limits of resolution ; both theory and experience show that the highest magnification of use is about 50 times the aperture in inches (thus, with a 3-inch telescope the highest useful power will be about $\times$ 150).

The amount of light collected by a telescope—ignoring losses through reflection at air-glass surface, by absorption in the glass, or through imperfect reflection—will depend solely on the area of the object-glass or mirror. Examination of Fig. IX. 9 will show that all the light passes through a disc situated a short distance behind the back lens of the eye-piece—the so-called *Ramsden disc,* which is in fact a real image of the object-glass formed by the eye-piece. Brief consideration will show that anything which prevents all this light passing through will effectively reduce the aperture of the telescope, and therefore both its light-collecting power and its resolving power, so that no aperture behind the Ramsden disc, whether a stop in the eye-piece mounting, or the pupil of the observer's eye, can have a less diameter than the disc if all the light collected is to be utilised. Since, as has been said, the Ramsden disc is the image of the object-glass formed by the eye-piece, it follows that with any given telescope there is a lower limit to magnification below which both light and resolution will lessen. Experiments have shown that the dark-adapted eye may have a pupillary opening as large as $\frac{1}{3}$ inch, from which it follows that the maximum size of Ramsden disc must not exceed this diameter, which is attained by a power not lower than three times the aperture in inches (so that the lowest useful power on a 3-inch telescope is about 10).

Reference may be made to the following works :

Bell, *The Telescope* (McGraw-Hill Book Co.), for a general account of the telescope.

Splendour of the Heavens, Vol. II (Hutchinson), for descriptions and illustrations of many famous astronomical telescopes and other information.

Amateur Telescope Making, and *Amateur Telescope Making, Advanced,* for much miscellaneous information on the construction of reflectors and refractors.

Glazebrook & Shaw, *Dictionary of Applied Physics*, Vo. III, for telescopes, etc.

Encyclopedia Britannica, IXth to XIIIth editions, for various articles on the Telescope, subsequent editions for the Periscope.

Couder et Danjon, *Telescopes et Lunettes*, for a general account, somewhat more detailed than Bell's.

SECTION 2

MEASURING INSTRUMENTS

CHAPTER X

DENSITY

The density of a substance is its mass per unit volume in any related system of measurement. Thus, commercially it may be stated in pounds per cubic foot, or scientifically as grams per cubic centimetre. Since the standard litre (the unit of volume) is not exactly 1 cubic decimetre (1,000 cubic centimetres) this relationship is more accurately expressed as grams per cubic millilitre (one thousandth part of one litre). Thus the density of water may be written as 1 gm./ml. or 62.4 lb./cu.ft. Nearly all substances sensibly change in volume, and therefore in density, with temperature, and thus it is necessary to specify the temperature at which measurements are taken. Commonly, 15° C., 20° C. and 60° F. are used.

Specific gravity (S.G. or sp. gr.) is the ratio of the weight of any volume of a substance to the weight of the same volume of some standard substance. The standard substance usually employed is water. In the example quoted above the S.G. of water would be $\frac{62.4 \text{ lb./cu.ft.}}{62.4 \text{ lb./cu.ft.}}$ which equals 1.000. Hence density expressed in the metric system is numerically equal to specific gravity, which is a pure number, the same whatever system of units be employed. For this reason the terms density and specific gravity are often in practice used as if they were mutually interchangeable. This, however, is not so: for density (gm./ml.) is defined directly and unambiguously in terms easily understood. The density of water is defined as unity at its temperature of maximum density, i.e. 4° C. It is 0.99823 gm./ml. at 20° C. With specific gravity, both the temperature of the substance and the temperature of the water, with which it is compared, need to be stated. Frequently the temperatures are written 15° C./15° C. indicating that the weight of a volume of the substance at 15° C. is compared with that of the same volume of water at 15° C.

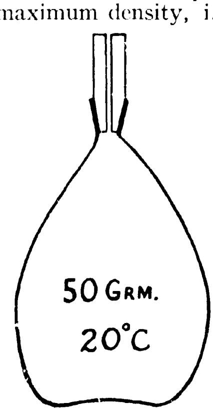


Fig. X. 1. Density bottle.

The methods used in determination of density are many and various. The method to be adopted for any given purpose is chosen largely with reference to the accuracy required and the speed with which the result is wanted. One of the most widely-used for liquids is the so-called density bottle, Fig. X. 1. This is a bottle of approximately a pear shape fitted with a carefully-ground glass stopper made from capillary, i.e. fine bore, glass tubing. Capacities in common use are 10, 25, 50, 100 ml. In use, the bottle is first completely filled with the liquid at room temperature. Insertion of the stopper causes liquid to be displaced and at the last twist the liquid rises in the bore of the capillary and the excess is forced out of the hole in the top.

When the outside of the bottle has been dried it contains a very accurately reproducible volume. It is then weighed on an accurate analytical balance, which has a sensitivity of 0.0001 gram. Subtraction of the known weight of the empty bottle gives the weight of the contents, and division of this value by the known volume of the bottle gives the density directly in gm./ml. at the temperature of the determination.

Temperature effects may cause errors of appreciable magnitude in determinations of this kind; for example, in the handling of the bottle during wiping, care must be taken that the temperature of the bottle is not raised, causing the liquid to be forced out through the capillary. In the most accurate work, after the bottle is filled, it is placed in a thermostatic bath, maintained at a slightly elevated temperature, for a period sufficiently long to enable the contents to assume the known temperature of the bath, which is then taken to be the temperature of the determination. If, during weighing, cooling of the bottle occurs, causing the meniscus (or surface) to recede in the capillary, no error is introduced, since the weight being measured is that of a volume adjusted to the bath temperature, which is the same both for the water and the unknown liquid. An error would, of course, occur if, during weighing, the temperature of the contents rose, causing the liquid to expand and to overflow through the capillary tube. Again, in accurate work, a buoyancy correction is introduced for the apparent loss in weight of the bottle due to its being weighed in air and not in vacuo. The measurement of specific gravity by this method, though highly accurate, is time-consuming. For many industrial and technological purposes more rapid methods are required.

Specific gravity beads, Fig. X. 2, though more commonly used in the last century than in the present, have a useful function. They are specially useful for rapid determinations where the quantity of liquid available may not be large. They consist of a small glass bulb, diameter usually 5-15 mm. If the weight of the bulb is less than the weight of the volume of liquid which it displaces, it will float on the surface: if the converse, it will sink. If the weight of the bulb is just equal to the weight of the volume of liquid which it displaces, it will remain in any position provided that it is fully immersed. The beads are often made with a weight/volume ratio differing by steps of 0.002. In practice a few of them, covering a range within which the S.G. of the unknown is expected to fall, are put into a sample of the liquid. Some will float, while others will sink. One bead will be found, which will display a tendency neither to rise nor to fall to any depth. This bead is the one that indicates the density of the liquid. It may happen that no bead is present which exactly corresponds with the density of the liquid and that all beads either float or sink. It is then obvious that the density is intermediate between the heaviest bead that floats and the lightest bead that sinks. In such a case if the liquid is slightly warmed or cooled one of the heavier or lighter beads will sink or rise, and will

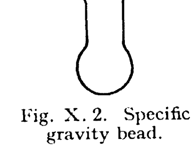


Fig. X. 2. Specific gravity bead.

enable the exact density to be determined at the temperature found to be appropriate. Beads of this type have found wide application to indicate when accumulators are in need of recharging. Since the state of charge of an accumulator is related to the acid density, which decreases as the accumulator becomes exhausted, an appropriate bead will float in the acid of a fully-charged accumulator. When the bead begins to sink a visual indication is provided that recharging will shortly be necessary, and much inconvenience is avoided by the timely warning.

The instrument most universally employed for density measurements is the hydrometer. There are very many types of hydrometer—the "density" hydrometer, the Baumé, Twaddell, Brix, Sikes, Nicholson instruments, while the barkometer, salinometer, lactometer, urinometer, alcoholometer, argentometer, saccharometer, etc., are all variants of the simple density hydrometer. In the main these latter are calibrated with special scales so that the strength in solution of a desired constituent is read from the scale without either tedious calculation or reference to tables. We shall consider here only the general form of density hydrometer with one or two particular illustrations, though it is obvious that where any property of a solid in solution is a function of the density of the solution, then a special hydrometer, with a scale direct-reading in that property, can be constructed. It must be said, however, that the tendency in recent years has been to abolish instruments with special scales and to standardise on hydrometers indicating density only, in gm./ml.

When a body floats in water under the action of gravity part of it is below the water surface and part above. The weight of water displaced by the part below the surface is equal to the weight of the whole body, i.e. the weight of the body is equal to the weight of water which it displaces. This principle is used in the construction of hydrometers.

Fig. X. 3. Hydrometer.

As formerly constructed, hydrometers were of the shape shown in Fig. X. 3. The small bulb contains either mercury sealed in the bulb, or lead shot embedded in a wax to fix it in position. This weight serves two purposes ; it is near the base and, therefore, confers the stability necessary to make the instrument float vertically and, by adjustment of the amount of the "poising," the instrument may be made to float so that a mark near the top of the stem coincides with the surface of a liquid of any desired density. This latter is of great importance in adjusting the range of the instrument. Modern forms of the instrument are shaped as in Fig. X. 4. They are more robust than the older type, settle more quickly to the work, have excellent floating characteristics and are not liable to errors with viscous liquids due to the trapping of an air bubble in the waist. As met with in commerce hydrometers are available for liquids ranging from about 0.60 to 2.0 in specific gravity, i.e. from the lighter hydrocarbons, benzole, etc., to sulphuric acid. Each instrument will cover a range of 0.05, 0.1 or 0.2 S.G., according to its sensitivity.

The sensitivity is fixed when the instrument is made and is a function of the displacement of the bulb and the cross-sectional area of the stem. Coarse instruments for works' use have a relatively large diameter stem, say 6—8 mm. More sensitive instruments have a smaller, 4—6 mm. diameter stem. Considerations of fragility preclude reduction of the stem diameter beyond certain limits, for the instrument is supported by the stem when it is being lowered into the hydrometer jar containing the liquid to be measured. To illustrate the sensitivity which can be obtained, however, by reduction of stem diameter, it may be stated that hydrometers have been constructed with a bulb 7.5 cm. diameter and with a wire stem only 0.5 mm. diameter. The addition of a weight of 0.065 gram to the top of the stem causes this instrument floating in water to sink by 25 mm. The usual practice, therefore, is to combine adequate sensitivity with the robustness consistent with that sensitivity. Such hydrometers are 6 in., 9 in. or 12 in. long and are sub-divided to read directly to 0.005, 0.002, 0.001 or 0.0005 gm./ml.

Fig. X. 4. Modern form of hydrometer.

One source of error in using hydrometers arises from uncertainty in locating the plane of flotation due to the rise by surface tension of the liquid around the stem as represented in Fig. X. 5. With transparent liquids it is often of assistance to read the meniscus from the underside of the surface. With highly-coloured liquids this is not possible, but with practice in allowing for the rise the error is much reduced. Tables are published (by the British Standards Institution, No. 718—1936) giving the corrections for liquids differing in surface tension by as much as 40 dynes/cm. for use with certain types of hydrometers. These hydrometers have been designed with great care so that the temperature correction within the range 10 to 30° C. does not exceed 0.0005 gm./ml.

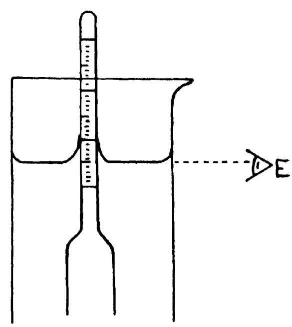


Fig. X. 5. Method of using hydrometer.

The Sikes Hydrometer, Fig. X. 6, is the standard instrument used by the Customs and Excise Department for assessing the duty to be paid on beer, wines and spirits through a specific gravity determination of the alcohol content. It furnishes an interesting illustration of extension of the range of a hydrometer, by the use of additional weights exterior to the instrument and applied to a stem near the base bulb. Sikes's instrument, being used in liquids which are non-corrosive, is made of metal, gilded, with a rectangular stem about 3½ inches in length. The weights are numbered 10, 20, 30 . . . 90 and in using the instrument a weight must be selected which will allow only a portion of the stem to be submerged. The emergent scale reading is then taken and is added to the denomination of the particular weight

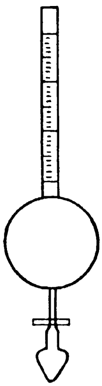


Fig. X. 6. Sikes hydrometer.

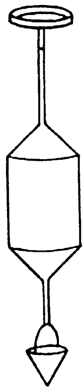


Fig. X. 7. Nicholson's hydrometer.

in use at the base. Comprehensive tables are then consulted to determine the alcohol content upon which the duty charge is to be based.

Nicholson's hydrometer (Fig. X. 7) is an illustration of a constant immersion-depth instrument which can also be used to determine the density of a solid by Archimedes' principle. It consists of a hollow, cylindrical metal body with a heavy, conical basket attached to the base. A small scale pan is attached to the top by means of a wire on which is a mark indicating the constant immersion depth. The scale pan always contains weights. To find the density of a solid heavier than water, the solid is placed on the scale pan and weights are added until the hydrometer sinks to the mark. The normal scale pan load minus the weights used when the solid is on the pan gives the weight of the solid in air. The solid is then transferred to the basket. It will now be found that the hydrometer will stand higher in the liquid. The weights to be added in this operation will be less than those in the first by the weight of water displaced by the immersed solid. Since the density of water is 1.0, the weight of water displaced in grams is numerically equal to the volume of the body in cubic centimetres. Thus, by a simple subtraction we have the weight of the body in air, and also its volume, whence the specific gravity of it relative to the liquid is evaluated. If the solid is soluble in water some liquid may be chosen in which it is insoluble. Similarly if it float in water, and be insoluble in alcohol, turpentine, etc., whichever is suitable of these liquids may be used.

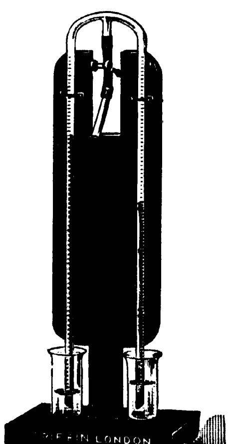


Fig. X. 8. Hare's apparatus.

Hare's apparatus (Fig. X. 8) provides a simple means of comparing the densities of two liquids with moderate precision. If the density of one of the liquids is known, then the density of the other can be evaluated. The apparatus consists of two graduated vertical tubes, connected together at their upper ends. In the connecting tube is a third tube by which air may be withdrawn from the apparatus. This tube is closed when not in use by a short length of rubber tube fitted with a spring clip. The liquids to be compared are contained in two beakers into which dip the open ends of the vertical tubes, On withdrawing air through the suction tube the liquids rise in the graduated tubes. Since these tubes are connected together at the top, the air pressure above the liquids in both tubes is equal. The pressure on the free surface of the liquids in the beakers is also equal, viz., that of the atmosphere. The difference

between the air pressures outside and inside the tubes just balances the heights of the liquid columns. Hence the difference in lengths of the liquid columns is inversely proportional to the densities of the liquids, i.e., the lighter liquid rises to a greater height than the heavier liquid. If tap water were one liquid, which rose 205 mm. in its graduated tube and sea water were the other, which rose 200 mm. in its tube, then the density of the sea water would be 1.025.

A very convenient and rapid method in wide use which is employed where an accuracy comparable with that obtainable with a density bottle determination is required, is the Westphal balance (Fig. X. 9). This comprises a beam, delicately balanced on a sharp knife edge, with its right-hand arm accurately divided into ten parts by nine notches, which serve to accommodate U-shaped riders. The beam is in equipoise when, from the hook at the right, there is suspended by a fine platinum wire a glass plummet, which displaces exactly 5 gm. of distilled water at 15° C. The plummet is usually hollow and contains a thermometer. The U-shaped riders weigh 5, 0.5, 0.05 and 0.005 gms. Immersing the plummet in distilled water at 15° C. the right-hand side of the beam experiences an up-thrust equivalent to the apparent loss in weight of the plummet. Placing a 5 gm. rider on the hook exactly restores equipoise at the 1.0000 position. If now the plummet is immersed in liquid of some other density the up-thrust is altered and the riders must be placed in other positions on

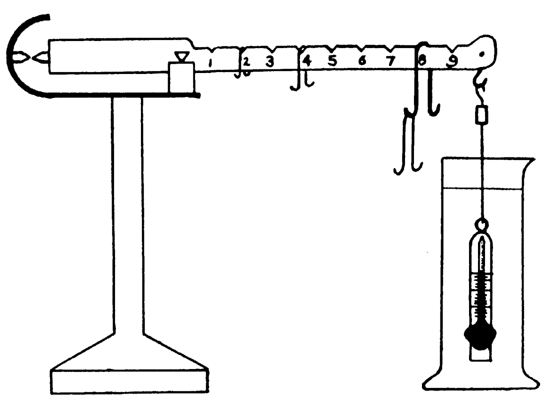


Fig. X. 9. Westphal balance.

the beam. In the illustration shown in Fig. X.9 the reading is 0.8842. For liquids of density heavier than water, one 5 gm. rider is placed on the hook and another 5 gm. rider, together with the smaller riders, is placed on the beam until equilibrium is obtained. The chainomatic-type of Westphal balance dispenses with the small riders, whose adjustment is tedious, by the use of a chain, suspended at one end from the beam, and at the other end from a vernier movable along a vertical, graduated column.

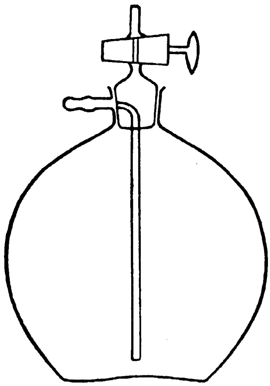


Fig. X. 10. Chancel flask.

The determination of the density of a gas is an operation more complex than that of liquids or solids. These latter, under normal density determination conditions, are regarded as incompressible and therefore the effects of variation in atmospheric pressure can be disregarded. With gases this is not so, as both atmospheric temperature and pressure exercise a considerable effect upon their volumes. The density of a gas is expressed as measured at N.T.P., i.e. the normal barometric pressure of 760 mm. at a temperature of 273° K. = 0° C. The straightforward method is by direct weighing, using a Chancel flask (Fig. X.10). The flask is first evacuated and weighed. It is then filled with the gas, the barometric pressure and prevailing temperature are recorded, and the flask is weighed again. The difference of the two weights gives immediately the weight of the gas, and if the volume of the flask is measured, by filling it with water, the weight of 1 litre of gas can be computed.

More rapid and practical is the type of specific gravity bell (Fig. X. 11) used largely in gasworks. This apparatus consists of an inverted bell provided at the top with a tube containing a platinum plate pierced with a minute hole (orifice plate). The open end of the bell is immersed in water in a surrounding container. Now the time required for a given volume of gas to diffuse through a small hole varies inversely as the square root of the density of the gas. This proposition is known as Graham's Law. In use, the bell is raised and is filled with air. If now the tap is opened, the air will diffuse through the orifice plate. The time is accurately measured for the pointer to pass between two marks on the scale plate. The procedure is repeated for the same volume of the unknown gas. The times of effusion, and the density of air being known, the density of the unknown gas is readily evaluated.

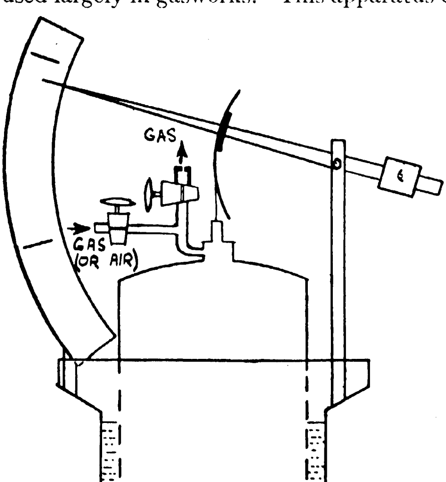


Fig. X. 11. Gas specific gravity bell.

CHAPTER XI

DIMENSION

The instruments described in this chapter are confined to those used for measuring small linear dimensions to a high degree of accuracy. There are many such instruments and they cover wide fields of application, such as the measurement of the diameter of a plug gauge to a degree of accuracy of 0.0001 in. or less, the thickness of a layer of chromium plating, the roughness of a machined or lapped surface, the small extension of a piece of material when stressed or heated, and the pitch of a screw thread. Many measuring instruments depend on obtaining a magnification of a small movement, which can be produced by mechanical, optical, electrical or hydraulic means. The very common measuring instruments must not be despised because of their simplicity. Simplicity is usually a commendable feature. A steel rule, for instance, if of reliable make, with care and the aid of a simple microscope, can be used for estimating measurements to 0.001 in. Internal and external calipers can be used to compare sizes to the same degree of accuracy. A flexible steel rule can be used to make an accurate measurement of the circumference of a large cylinder. Measuring instruments are designed not only with the motive of making accurate measurements, by producing large magnification or reducing the human error in sight and touch, but also to enable measurements to be made quickly.

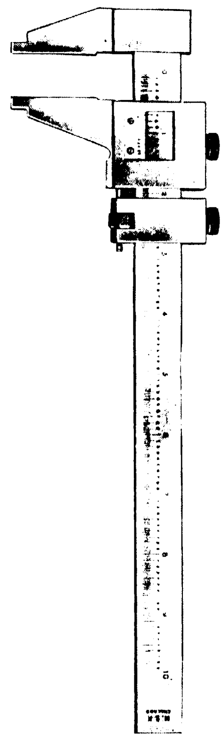


Fig. XI. 1. Vernier caliper.

The Vernier Caliper

A vernier caliper (Fig. XI. 1) can be used for making external and internal measurements to a degree of accuracy of 0.001 in. or 0.02 mm. One of the jaws is made integral with one end of a flat beam usually graduated in divisions of 1/40 in. or ½ mm. The other jaw slides along the beam and carries the vernier scale with 25 divisions, thus permitting a measurement to be made to 0.001 in. or 0.02 mm. The sliding jaw is connected to an auxiliary slide by means of a fine screw and knurled nut. By clamping the auxiliary slide to the beam and turning the knurled nut the vernier can be accurately adjusted.

It is not easy to get the "feel" of a job between the jaws of a vernier caliper, considerable skill being required to make a measurement to the finest degree of accuracy.

The Vernier Height Gauge

A graduated scale is attached perpendicular to a base plate the upper and lower surfaces of which are finished to a higher degree of accuracy. In some height gauges a small flat-topped hard steel button is fixed to the top surface. A sliding jaw with a vernier scale, coupled to an auxiliary slide moves along the vertical scale and measurements are made between the sliding jaw and the button, or between the sliding jaw and the bottom surface of the base plate. The scales are graduated in the same way as for the vernier caliper. The height gauge is used mostly on a surface plate, and a scribing attachment can be fitted to the sliding jaw which facilitates accurate marking out.

The Micrometer

The micrometer (Fig. XI. 2) is one of the most common and most useful of measuring instruments and the micrometer screw is embodied in many ways in different kinds of instruments. An external micrometer indicates the distance between an anvil, which is fixed to the micrometer frame, and the spindle, which moves relative to the anvil. A screw thread is cut on one end of the spindle, which turns in an internal thread cut in the barrel which is integral with the micrometer frame. The barrel is graduated on its outside surface with a scale of 0 to 1 in. by fortieths of an inch. To the screwed end of the spindle is attached the thimble which fits over the barrel, and is used to turn the spindle. Thus, for one complete turn of the spindle, the thimble edge moves along the barrel a distance equal to the pitch of the screw which is one-fortieth of an inch. The thimble edge is graduated into 25 equal divisions, the graduations registering against a base-line on the barrel scale, and so a turn of one thimble division equals a spindle movement of 0.001 inches. For metric measurement, the pitch of the screw is $\frac{1}{2}$ mm., and the thimble is graduated into 50 divisions, thus giving a reading of 0.01 mm. for one thimble division.

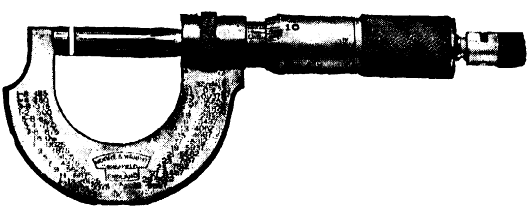


Fig. XI. 2. 0–1 in. external micrometer.

The accuracy of a micrometer is limited by the accuracy of the screw pitch, the flatness of the anvil and spindle faces, and the parallelism of the anvil and spindle faces for all screw positions. Care must be taken, when making a measurement, in getting the "feel" of the job between the measuring faces, and the thimble must be rotated slowly so that the measuring faces are just touching the job, without any spring in the instrument. To reduce this human error a friction drive is sometimes incorporated in the thimble, in which case the thimble is turned by means of a small knurled projecting knob which slips when contact is made between the job and the measuring faces. With a well-made micrometer a measurement can be estimated to 0.0001 in., a vernier scale being sometimes engraved on the barrel to aid such estimation.

The total travel of a micrometer screw is limited to one inch, owing to screw pitch inaccuracies and constructional difficulties, hence micrometers are made to measure from 0 to 1 in., 1 in. to 2 in., 2 in. to 3 in., etc.

In order to facilitate an accurate measurement to 0.0001 in. and to eliminate the human element in getting the feel of the job, a movable anvil is sometimes used. Any anvil movement is transmitted through a magnifying mechanism to a dial in the frame of the micrometer. The dial is graduated in divisions, each division representing an anvil movement of 0.0001 in.

A useful type of internal micrometer (Fig. XI. 3) consists of a micrometer screw, barrel and thimble, graduated as for an external micrometer.

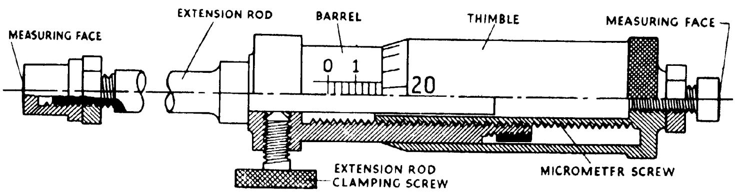


Fig. XI. 3. Internal micrometer. The range of the micrometer screw is 0.5 in. The extension rods increase in length by 1.0 in. increments, and a 0.5 in. length extension collar can be inserted between the shoulder on the extension rod and the barrel.

To the open end of the barrel a rod is fixed called an extension rod, the projecting end of which constitutes one of the measuring faces, the other face being at the end of the thimble. The measuring faces are curved to a radius of curvature of just less than the smallest measurement which can be made with the instrument. Extension rods of different sizes can be fitted to vary the range. A typical internal micrometer would have a micrometer screw with a range of $\frac{1}{2}$ in., the total range by the use of extension rods being from 2 to 6 inches. The use of an internal micrometer requires more skill than an external micrometer, particularly for large measurements, a degree of accuracy of 0.0005 in. being reasonably good.

Bench Micrometer

A bench micrometer is designed for greater accuracy than a hand micrometer, and as the name implies, is not portable, but fitted to a bench or table. Greater accuracy is obtained by having a much larger thimble and some sort of moving anvil, small anvil movements being magnified and indicated by means of a pointer on a dial. With a 0.025 in. micrometer screw pitch and 250 divisions on the thimble the micrometer would read direct to 0.0001 in. When used as a comparator a degree of accuracy of 0.00002 in. can be obtained.

Dial Gauges

A dial gauge is an instrument in which the movement of a plunger is transmitted through a mechanism which magnifies the movement, and

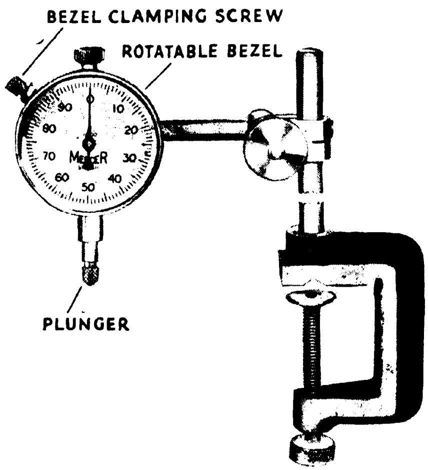


Fig. XI. 4. Dial gauge mounted on clamp.

indicates it by means of a pointer on a circular dial (Fig. XI. 4). The dial is usually about 2 ins. in diameter. Two types of magnifying mechanisms are commonly used. In one, the plunger actuates a toothed sector which drives a small pinion to which the pointer is attached. Backlash is prevented, and the plunger kept in contact with the sector by means of springs. This type does not permit a large plunger movement, which is usually restricted to one dial revolution. In the other type, a rack is cut on an extension of the plunger, which actuates a gear train terminating in the pointer spindle. A tension spring keeps the plunger in the fully-extended position. This type permits larger plunger movements, usually up to $\frac{1}{4}$ inch, and larger for special purposes.

The usual dial graduations are 100 divisions of 0.001 in. each, 50 divisions of 0.001 in. each, 100 divisions of 0.01 mm. each, and 100 divisions of 0.0001 in. each. A useful form of dial graduation is 100 divisions marked 0 to 50 and 50 to 0 ; this form is very useful for indicating plus or minus errors.

The dial is fitted with a rotatable bezel and clamping screw, which facilitates zero setting. The plunger is fitted with a removable contact point, and the gauge is fitted with a lug for attachment to a comparator or scribing block stem.

Dial gauges are most usefully employed as comparators, i.e. for the measurement of small differences in dimensions. This is because the degree of error increases with the plunger movement, and may amount to 1 division over a complete dial revolution.

Slip Gauges

A slip gauge is a block of hardened steel, usually in the shape of a rectangular prism, two opposite faces of which, called the measuring faces, are a known accurate distance apart, this distance being the length of the gauge. The measuring faces are flat and parallel to a high degree of accuracy, and are finished to a high degree of smoothness. A set of slip gauges consists of a number of pieces of different lengths, which by various combinations can be used to build up a wide range of lengths.

The high degree of smoothness and flatness of the measuring faces is necessary in order that two gauges may be wrung together. The phenomenon known as wringing is of great importance in metrology,

and the many uses of slip gauges depend upon it. If two sufficiently flat and smooth surfaces are pressed together with a sliding action, and a thin film of fluid exists between the surfaces, the two surfaces will adhere to the extent that a force of as much as 100 lbs. per square inch of surface may be required to separate them. The conditions for wringing are that the surfaces have a high degree of polish, a similarity of curvature to within 0.00001 in. at the centres of the surfaces, and a thin liquid film of the order of 0.0000003 in. thick. Chemically clean surfaces will not wring.

Considerable care must be exerted in the use of slip gauges. It is not advisable to touch the measuring faces with the hand, and the grease used to enable wringing to take place must be very clean and free from corrosive matter. The length of a slip gauge is actually defined as the distance between its top surface and a surface upon which it has been wrung. Thus the length includes the thickness of one wringing film.

The length is made to a degree of accuracy dependent upon the use to which the slip is to be put, i.e. whether for workshop use, inspection or reference. The highest degree of accuracy is two parts in a million. If two piles of the same nominal dimension are made and wrung on to a common surface, side by side, a slip can be wrung on to the top surfaces of each pile, if the two piles are of the same length to within 0.00001 in. (.00025 mm.).

Various accessories are available for use with slip gauges, and they are usefully employed in conjunction with a sine bar for the accurate setting out of angles.

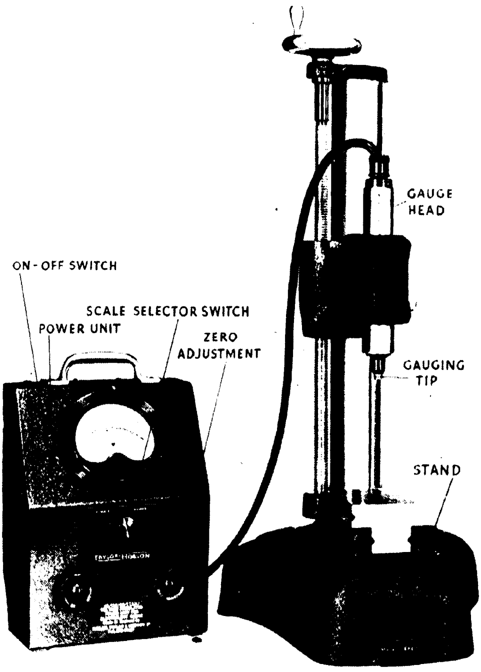


Fig. XI. 5. Electrolimit comparator.

Electrically Operated Gauges

The Electrolimit comparator (Fig. XI. 5) is an instrument for measuring small differences of length. It consists of three essential parts,

the stand, the gauge head and the power unit. The stand is of robust construction and consists of a base on which is fitted a hard steel anvil, the upper surface of which is serrated and optically flat, and a vertical column of ten inches height. The gauge head, 6 in. long and $1\frac{1}{4}$ in. diameter, is held in a split jacket which fits round the column. It can be adjusted to any vertical position by means of a screw, and fixed by means of a locking screw. The gauge head contains a coil and plunger mechanism, at the lower extremity of which is the gauging tip. There are various forms of gauging tips which are interchangeable. A vertical movement of the gauging tip causes the displacement of an armature and induces an alteration in the inductance value of two coils in the electrical circuit. A microammeter in the power unit records the amount of current flowing in the electrical circuit, which is proportional to the displacement of the gauging tip. Hence the microammeter scale is calibrated to indicate directly the displacement of the gauging tip.

The method of operation is as follows. The power unit is connected to the electrical mains supply, and a master reference block of thickness equal to the required dimension is wrung on to the anvil. The gauge head is then lowered so that the gauging tip is in contact with the master gauge and zero is registered on the scale. The gauge head is then locked in position. The gauge head adjusting screw is not sensitive enough to obtain an exact zero setting, hence a fine zero adjusting knob is provided in the power unit, by which the final setting is made. The article to be measured then replaces the master gauge, and any deviation in size is registered on the scale.

A magnification, i.e. the ratio of the meter pointer movement to the corresponding gauging tip movement, of 10,000 can be obtained with instruments of this type. Dual range instruments are made, in which the scale is calibrated for two separate magnifications, a switch in the power unit controlling the scale in use.

There are other types of measuring instruments which use this principle. The caliper gauge is a portable instrument and can be used for measuring work without removing it from the machine. The continuous thickness gauge or "flying mike" is used for measuring the thickness of rolled metal strip or plate as it emerges from the rolling mill. A continuous reading to 0.0001 in. is indicated and facilitates roller setting without stopping or slowing down the mill. The surface roughness measuring instrument plots the profile of a surface automatically, with a magnification that can be varied from 400 to 100,000.

Solex Air-Operated Gauge

A supply of compressed air is necessary for the operation of this instrument (Fig. XI. 6). The air pressure is governed by a device called the air controller, which is essential in order to maintain a constant pressure. The air is led from the controller through an orifice called the control jet, and into a chamber, from which it passes through another orifice, called the measuring jet, to the atmosphere. The measuring jet is variable in size, but is always much larger than the control jet, thus the air pressure in the chamber is between the controlled pressure and the atmospheric pressure, and will depend on the size of the measuring jet. The size or opening of the measuring jet is controlled by its proximity

to the surface of the article being measured. A manometer registers the chamber pressure and is provided with a scale which is calibrated to indicate the distance between the measuring jet and the surface being measured or, more generally, the size of the part. A master gauge of a known size may be used as a reference to check the zero of the scale.

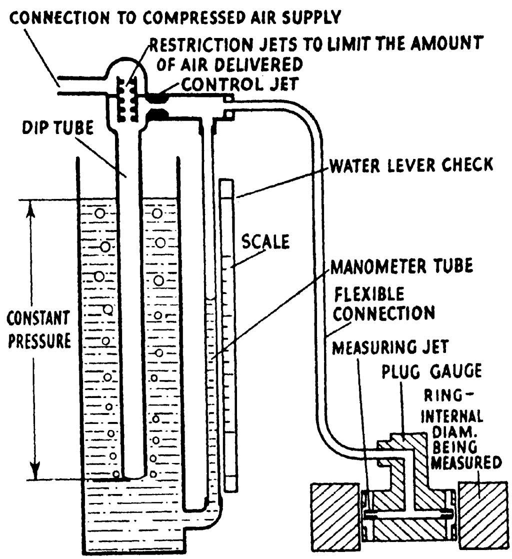


Fig. XI. 6. Solex air operated gauge.

Magnifications most suitable for this instrument are from one thousand to ten thousand, but a magnification of 100,000 can be obtained for special work.

This instrument can be adapted for use in various forms. The gauge unit can be attached to a comparator stand and used as a distance gauge. It can also be used in the form of a thickness gauge, a plug gauge and a ring gauge. A special feature, apart from its accuracy, is the absence of wear on the gauge unit. For instance, an ordinary plug gauge has to withstand considerable wear and becomes useless after a certain number of passes ; whereas a Solex plug gauge is made considerably smaller than the part being measured, the measuring jets, two in this case, diametrically opposite, being recessed in the gauge surface, thus never coming into contact with the part being measured.

A new manometer calibration must be determined for each dimension being measured, hence this type of gauge is most suitable for the measurement of a large number of identical articles.

Travelling Microscope

End measuring instruments measure the distance between two faces of an article by contacting the faces with the measuring faces of the instrument. Such instruments cannot be used for measuring the distance between two lines or points on a surface, and not always for measuring the distance between two faces. A line measuring instrument must be used for such purposes, the travelling microscope being an example of such an instrument. A cross wire in the microscope is aligned with the two points or lines in turn, the distance between the points being either

the distance moved by the microscope, if the article being measured is held stationary, or the distance moved by the article, if the microscope is held stationary.

In a typical instrument the microscope is held with its axis vertical and is movable in a horizontal direction, the movement being controlled by a micrometer screw of 1 mm. pitch, there being 100 divisions on the drum and a range of 40 mm. The article being measured is held rigidly on a table which can be adjusted to the correct position.

The range of a travelling microscope is limited by the pitch accuracy of the micrometer screw, and the difficulty of ensuring that the distance moved by the screw is exactly equal to the travel of the focal point of the microscope.

A co-ordinate measuring microscope measures distances in two directions at right angles to each other. The microscope is carried on a compound slide which allows a one-inch movement in the two directions. The slide is rigidly fixed to the instrument bed. The table carrying the article being measured is also attached to the bed, but can be moved along the bed, any such movement being measured by means of end gauges laid in a groove between the table and a stop on the bed. A 12 in. displacement is obtainable in this way.

Extensometer

An extensometer is an instrument which measures very small changes of length, mainly in tests on material under compression or tension. There are a number of important conditions which influence the design and construction of an extensometer. For example, it might be required to measure the increase of length over an 8 in. length of a 1 in. diameter steel test bar, when placed in a tensile testing machine and subjected to progressive tensile loading up to 10 tons or more. Measurements of the extension must be made progressively so that a load-extension curve can be plotted. Sometimes this curve is plotted automatically by a piece of auxiliary apparatus called an autographic recorder. The extensometer must be capable of recording extensions of 0.0001 in. or less, it must be robust in construction, light, the means of attaching it to the test piece must be such that little deformation of the test piece surface is made, and the moving parts must be so designed to reduce backlash to a minimum. The keynote of good extensometer design is simplicity.

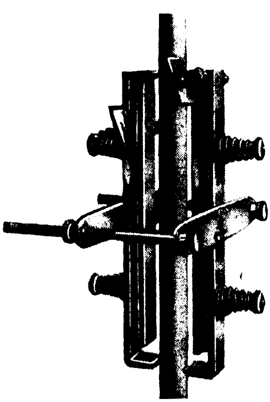


Fig. XI. 7. Lamb's roller extensometer.

The Lamb roller extensometer (Fig. XI. 7) is a type which has many commendable features. It consists of two similar parts which are fixed, by means of a common clamp, to opposite sides of the test piece. Each part consists of two flat bars, and each bar has a right-angle bend at one end, this end being shaped to a knife edge. Each bar makes contact with the test piece on its knife edge, and the bars are shaped and held so that a

space is left between the flat portions, into which a small hard steel roller is fitted. The bars can move relative to each other, such movement, however, when the extensometer is clamped in position, can be induced only by relative movement of the knife edges. Hence, when the test piece extends, the plates move relative to each other and the roller rotates through a small angle. A small mirror is attached to the roller and a beam of light directed on to the mirror and reflected on to a suitable scale, indicates the extension. By using a pair of extension elements, the average of the extensions on each side of the test piece is measured, the beam of light being directed from one mirror to the other and thence to the scale. On a test length of 8 in. an extension of 0.00001 in. is accurately recorded by this instrument.

Measurement by Interferometry

The phenomenon known as optical interference is used for the measurement of the flatness of a surface, for comparing lengths, and for making absolute measurement of length. Interferometers are described in detail in Chapter VII.

CHAPTER XII

ELECTRICAL

The enormous development of electrical engineering and the electrical industry has been very largely due to accurate measuring instruments. Instruments for indicating the presence of electric currents or charges have been used since the discovery of frictional electricity, but prior to 1888 the tangent galvanometer illustrated in Fig. XII. 1 was the only instrument which could be used for the accurate measurement of a quantity of electricity. Some modern instruments can measure currents as small as one million-millionth of an ampere, while others can measure the output of a large power station.

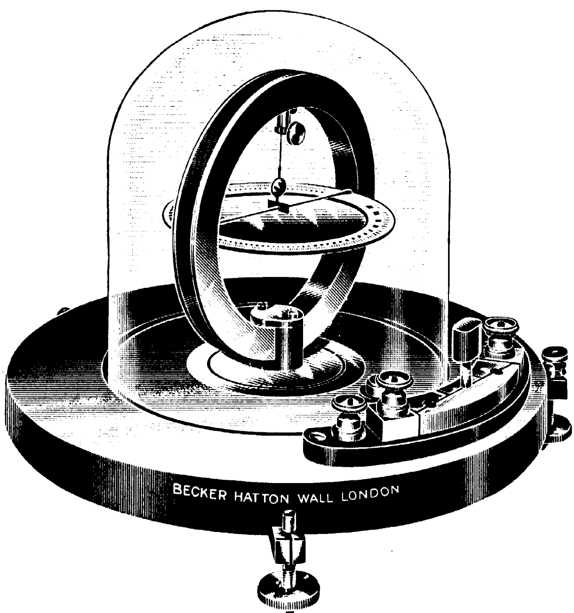


Fig. XII. 1. Tangent galvanometer.

A measuring instrument measures the magnitude of one property of an electric current or charge, and instruments may be classified according to the property which they measure, namely (1) The magnetic effect—this class includes moving magnet, moving iron, moving coil, dynamometers and induction instruments, all of which depend for their action upon the magnetic field of a current. Most of the instruments in general use are of this type. (2) The heating effect, including hot-wire and

thermo-couple instruments, which depend for their action upon the heating of a wire carrying a current. (3) Electrostatic, including voltmeters and precision wattmeters, which depend on the attraction between electric charges. (4) The chemical effect; the only measuring instrument of this type is a supply meter which measures the quantity of electricity passing through it, by measuring the amount of metal transferred from positive to negative in a solution.

Most instruments have a moving system, suspended or pivoted in jewelled bearings which can be twisted through an arc of 90° to 270°. The magnetic, thermal or electrostatic effect is made to exert a torque on the moving system, which turns until the deflecting torque is balanced by a controlling torque exerted either by a spring or gravity (Fig. XII. 2). The angle of deflection is indicated by a pointer attached to the moving system, or by a spot of light reflected from a mirror attached to the moving system, and is a measure of the current or voltage under test. For satisfactory working a damping torque is required, as otherwise the system would oscillate like a pendulum before coming to rest. This damping torque is operative only while the system is moving; Fig. XII. 3 illustrates the various component parts.

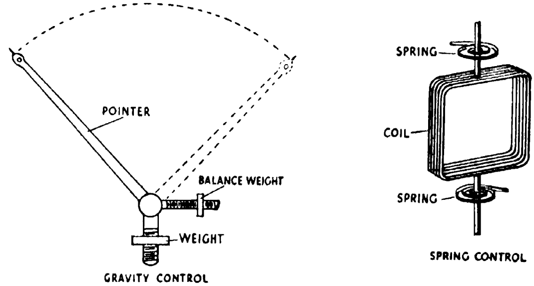


Fig. XII. 2. Diagram of spring and gravity control.

Shunts. The term shunt is generally applied to a low resistance which diverts a known portion of the current from a measuring instrument such as an ammeter. The name is also given to the high resistance placed in series with the instrument to increase the range of a voltmeter. They are chiefly used on D.C. instruments of the moving coil type, in order to make multi-range instruments. Shunts are sometimes used to increase the range of A.C. ammeters or wattmeters, but this is generally done by current or voltage transformers.

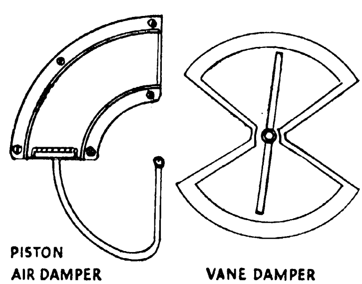


Fig. XII. 3. Two types of air damping piston and vane.

Moving Coil Permanent Magnet Instruments

In these instruments a light rectangular coil of fine wire wound on a frame of copper or aluminium is mounted on a spindle, so that its sides lie in the air gap between the two poles of a permanent magnet, and a

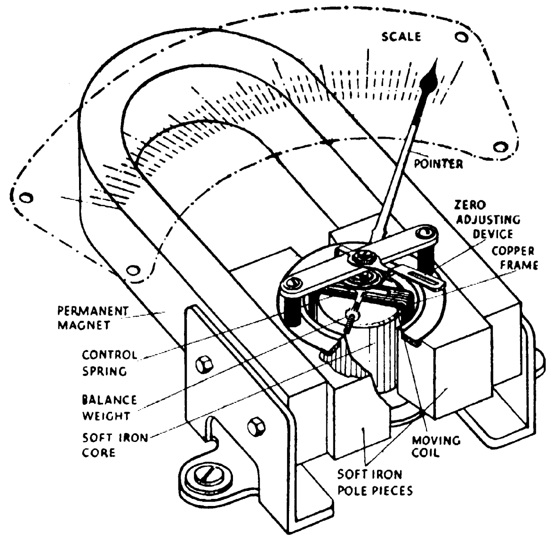


Fig. XII. 4. Diagram of moving coil permanent magnet instrument.

soft iron cylinder (Fig. XII. 4). The deflecting torque is produced by the reaction between the magnetic field of the coil and the uniform magnetic field in which it lies. The current is led into and out of the coil by means of two control springs; these springs supply the controlling torque. Damping is electromagnetic; the copper or aluminium frame moving through the magnetic field has an e.m.f. induced in it in such a direction that the current flowing round the frame sets up a torque opposing motion; the reading is "dead beat," i.e. its pointer does not oscillate. The scale of these instruments is uniform, because the deflecting torque is proportional to the current. These instruments can only be used on direct current.

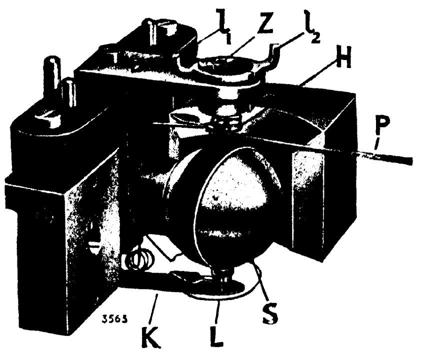


Fig. XII. 5. General arrangement of unipivot moving coil instrument.
S = Spherical core.
H = Control spring.
K = Lifting device.
L = Phosphor-bronze ligament.
Z = Zero-adjusting device.
P = Pointer l_1 and l_2 = projecting lugs.

Unipivot Moving Coil Instrument

In this instrument, illustrated in Fig. XII. 5, the coil swings concentrically round a spherical iron core mounted between the poles of a permanent magnet. The current is led in through the cylindrical spring and out through the flexible ligament, Fig. XII. 6. The pointer and counter weights attached to the top of the spindle are so arranged that the centre of gravity of the moving system coincides with the point of the pivot. This type is extremely sensitive, though by fitting different control springs the

sensitivity can be altered. Damping is electromagnetic.

Both the above types can be used as ammeters, voltmeters or galvanometers. In the case of ammeters the resistance of the meter must be low, to reduce the power loss (I^2R). In the case of voltmeters the resistance must be high to reduce the power loss. With a galvanometer the resistance can be high or low, depending upon the purpose for which it is to be used. A moving coil instrument can be made up into a multi-range instrument by means of shunts and switches, reading say, microamperes, milliamperes and millivolts, or milliamperes, amperes, millivolts and volts.

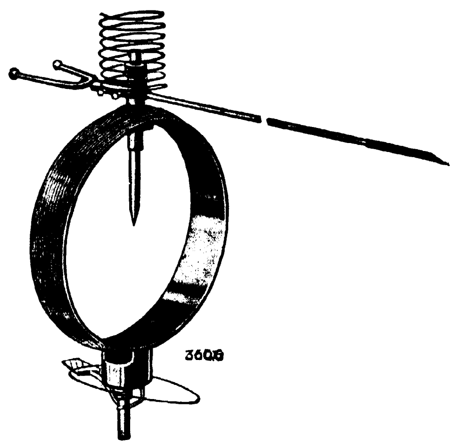


Fig. XII. 6. Coil of unipivot moving coil instrument.

Moving Iron Instruments

These instruments can be divided into two types—the Attraction type and the Repulsion type. Fig. XII. 7 illustrates both types. In the first type the deflecting torque is produced by a piece of soft iron mounted

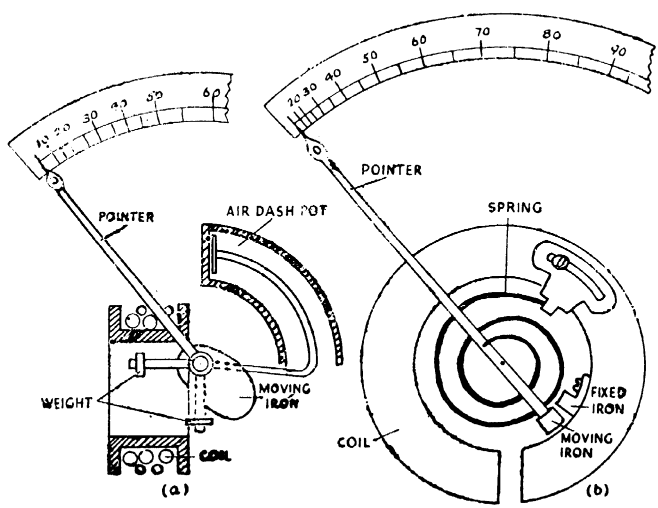


Fig. XII. 7. Diagram of moving iron instruments.
(a) attraction type, (b) repulsion type.

eccentrically on the spindle ; this is drawn into the coil when a current passes through the latter. In the second type, the deflecting torque is produced by the repulsive force between two similarly magnetised pieces of iron, one of which is fixed and the other mounted on a spindle. Most modern instruments are of this type. The deflecting torque is practically proportional to the square of the current (I^2), and inversely proportional to the square of the distance between the two pieces of iron. The scale, therefore, is unevenly divided and crowded at the lower end. By using specially-shaped pieces of iron, the scale can be improved. As reversal of the direction of the current only reverses the polarity of both pieces of iron, the instrument can be used on either direct or alternating current circuits. The controlling torque of these instruments may be either gravity or spring. while the damping torque is produced by air friction. The accuracy of these instruments is not the same on A.C. as D.C. These instruments, unlike the moving coil are liable to be affected by stray fields unless shielded by an iron case.

Owing to improved design and construction, the moving iron type of instrument now has an accuracy of the Sub-Standard and First Grade Ammeter and Voltmeter as laid down in British Standard Specification No. 89.

Dynamometer Instruments

In this type the permanent magnet of the moving coil type is replaced by two fixed coils, which provide an almost uniform field. The moving

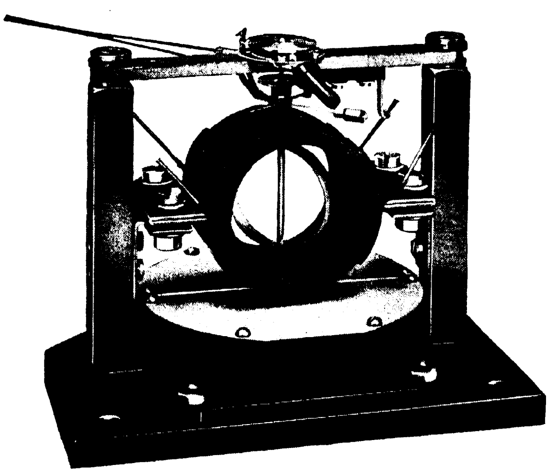


Fig. XII. 8 Dynamometer instrument.

coil is pivoted so as to swing freely in the magnetic field of the fixed coils and carries a pointer which moves over a scale. The controlling torque is a spring and the damping torque is produced by air friction. Fig. XII. 8 illustrates a typical instrument. In ammeters and volt-

meters, the three coils are connected in series. The scale of this instrument is uneven, as the torque is nearly proportional to the square of the current (I^2). This type of instrument can be used with equal accuracy on either A.C. or D.C. For various reasons, such as power consumption, change in calibration due to frequency, etc., ammeters and voltmeters of this type are only used for laboratory work. It is as wattmeters, both indicating and recording, that they are chiefly used.

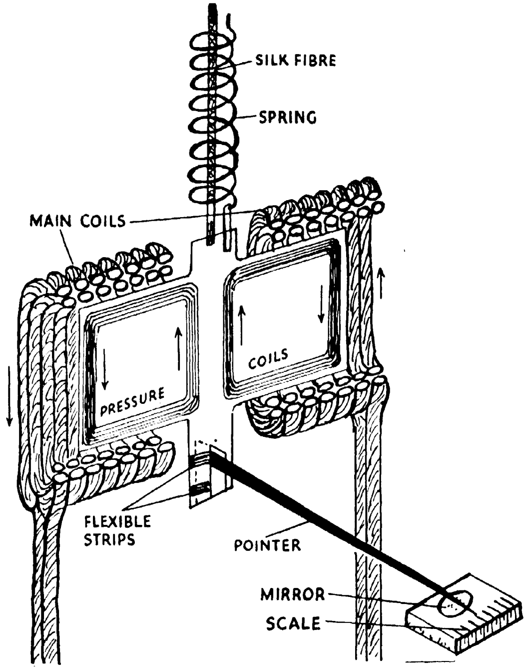


Fig. XII. 9. Standard wattmeter dynamometer type.

If the current to be measured, or a portion of it, is passed through the fixed coils, and a current proportional to the applied voltage is passed through the moving coil, the torque at any instant will represent the power at that instant, and the average torque shown on the scale will be the true power of the circuit, whatever the form of the current and voltage waves. Some dynamometer instruments use a high-grade nickel-iron alloy for the magnetic system. The eddy current and hysteresis losses are small and the instrument is almost unaffected by external field.

Universal dynamometers are also manufactured; these instruments can be used as ammeters, voltmeters and wattmeters. A standard wattmeter of the dynamometer type is illustrated in Fig. XII. 9. For measuring polyphase power under commercial conditions, instruments with two and three elements are made. Where a wattmeter is used to measure power in a circuit of very low power factor, an astatic type of wattmeter is used. The normal accuracy of these instruments conforms to British Standard Specification.

Thermal Instruments

These instruments fall into two classes, thermo expansion or "hot-wire," and thermo-couple. In the thermo expansion pattern, the quantity of current passing through the movement is measured by the degree of expansion produced by the heating effect of the current.

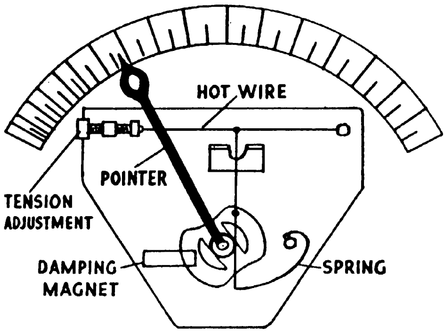


Fig. XII. 10. Diagram of hot wire instrument.

Fig. XII. 10 illustrates one type of instrument. The expansion wire is made of platinum-iridium wire. The sag in the wire due to expansion is taken up by a phosphor bronze wire, and attached to this is a silk fibre which passes round a small pulley on the spindle carrying the pointer. The whole system is kept taut by a spring. Although this type of instrument is sluggish in action, in order to get rid of jerkiness in operation, a damping device is fitted which consists of an aluminium disc moving between the poles of a permanent magnet. The scale of these instruments is uneven and crowded at the lower end. The power consumption of these instruments is considerable, being about four times that of a moving coil instrument.

The instrument has certain advantages as well as disadvantages. The supreme advantage is that it is completely independent of change in frequency or wave form ; it can be calibrated on D.C. and used without any alteration on A.C. of any frequency. It is therefore used extensively on high frequency work, such as wireless. The disadvantages are sluggishness in operation, wandering of zero position due to change in room temperature, and burning out of the instrument due to overloading.

The Thermo-Couple Instrument. This depends upon the fact that in a closed circuit containing dissimilar metals, a current will flow if the temperatures of the two junctions differ. If a moving coil ammeter is placed in such a circuit, it will measure the current flowing, when the temperature of one junction is raised by means of a heater. The current to be measured is passed through this heater and the other function is kept at a constant temperature. Fig. XII. 11 represents the general arrangement of such an instrument. To increase the sensitivity of these instruments, several thermocouples in series grouped round one heater are used and for high-grade work the single thermocouple is mounted in a vacuum, to reduce heat losses. The heater is made of a plain strip so as to be absolutely non-inductive and non-capacitance. The accuracy of this type of instrument for radio frequencies is superior to that of the hot wire instrument. Wattmeters using both the above-mentioned principles have been developed.

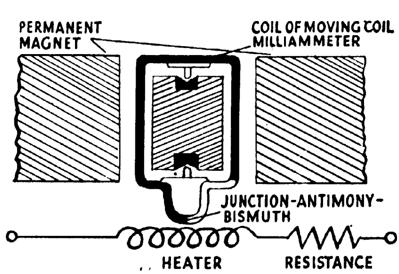


Fig. XII. 11. Diagram of thermo-couple instrument.

Induction Instruments

These instruments do not possess the same high degree of accuracy as the instruments already described, but their robust construction and long scale 300° or more has resulted in their very general use for alternating current switchboard work. Fig. XII. 12 illustrates the general principle of the instrument, first described by Professor Ferraris in 1885. In this case the instrument is wound as a voltmeter. Two opposite poles are wound in series with a non-inductive resistance and produce a flux in phase with the line voltage. The other two poles are wound in series with a highly-inductive resistance; these produce a flux which lags a quarter of a cycle approximately behind the line voltage. In between the poles is a disc or cylinder, somewhat similar to the rotor of a squirrel cage motor. The rotating field in this cylinder produces eddy current in it, and so the cylinder tends to follow the field round. This gives a torque, which is opposed by a spring, the resulting deflection being shown by a pointer moving over a scale.

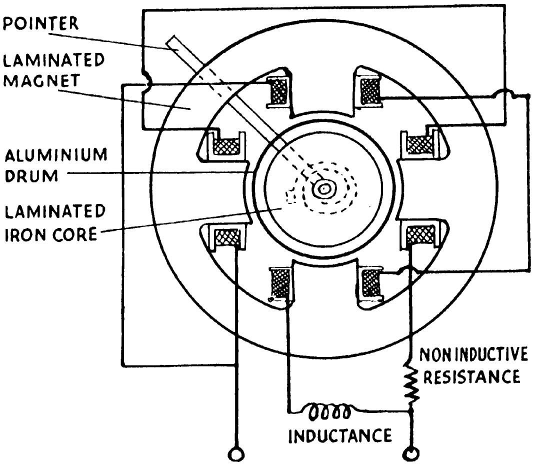


Fig. XII. 12. Induction instrument.

Another method of achieving this is the "shaded" pole, of which Fig. XII. 13 illustrates the general principle. In this instrument a laminated core is used, with a "shaded" pole, that is, one of the poles is surrounded by a heavy copper ring. A portion of the face of the iron core is cut away; this divides the magnetic circuit into two parallel paths and round one of these is placed a copper ring called the "shading" ring. This reduces the resistance and reactance to a minimum and causes the flux passing

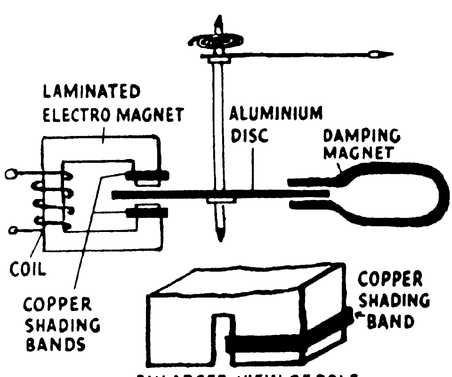


Fig. XII. 13. Diagram of induction instrument "shaded" pole type.

through this portion to lag behind the flux through the unshaded portion by an angle θ. The disc therefore has a current induced in it, and the torque produced is proportional to the square of the current. The controlling force is a spring, and damping is by electromagnetic induction provided by a permanent magnet. The graduations on the scale of these instruments are not equal, but can be made nearly so over the major portion of the scale, by cutting away some of the disc. These instruments should only be used on the frequency for which they are calibrated. They have the advantage of very long open scales.

Induction wattmeters involve the same general principles as already described. Fig. XII. 14 illustrates the general principle of such a meter. A laminated electro-magnet has at the bottom one large pole series wound, and carrying the line current, while above are two smaller poles which are shunt wound and are connected across the line by a circuit which is made as inductive as possible. In this way, when working on a unity power factor load, the two fluxes will be a quarter of a cycle out of phase. At power factors other than unity, the two fluxes will not be exactly in quadrature, and the torque produced will be less. This gives a lower reading corresponding to the lower value of the true power E.I. Cos Φ. The power consumption of these instruments is fairly high.

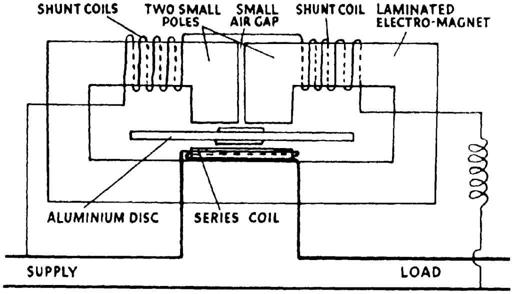


Fig. XII. 14. Diagram of induction wattmeter.

Electrostatic Voltmeter

The principle of this instrument is the force of attraction between two bodies, between which a potential difference is maintained. The voltage is measured by the relative movement of two or more plates, between which the potential difference to be measured is established. In the normal type of electrostatic voltmeter, the force of attraction is directly proportional to the square of the distance between the surfaces, the exposed area of the surfaces, the specific inductive capacity of the medium between the surfaces, and inversely proportional to the square of the distance between the surfaces.

Electrostatic voltmeters are of various types. One type only will be described, that of the attractive disc type. Fig. XII. 15 illustrates the Kelvin multicellular voltmeter. It consists of two sets of vanes, one fixed in a horizontal position, equally spaced, and the other the movable set attached to a vertical spindle ; both the fixed and moving vanes are made of aluminium. The movable vanes rotate symmetrically between the fixed vanes. The whole moving system is supported by a fine platinum-iridium wire attached to the top of the spindle,

while the other end is connected to the torsion head; this enables the pointer to be adjusted to the zero position. The pointer is attached to the spindle and moves over a horizontal scale. At the bottom of the spindle is a damping vane which rotates in an oil bath. This type is suitable for laboratory work, but a modified form is made for commercial use. The range of these instruments can be increased by using one or more condensers in series with the instrument.

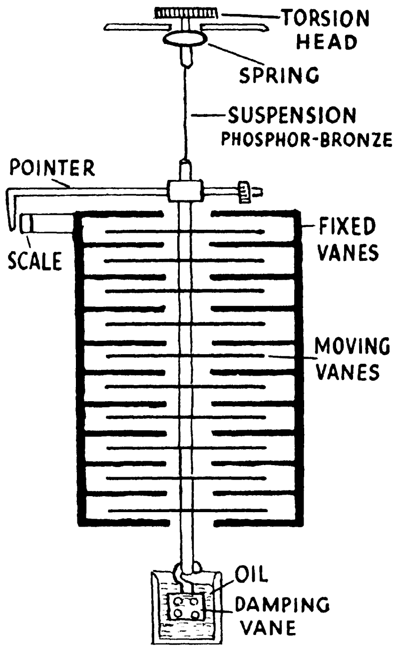


Fig. XII. 15. Kelvin multicellular electrostatic voltmeter.

By suitable shaping of the moving vane, a fairly open scale above a quarter or a third of the full scale reading can be obtained. They can be built to sub-standard accuracy. The chief errors are those due to mechanical sources, resulting from the smallness of the working forces. Except for stray electrostatic fields (from which they can be shielded), they are immune from errors due to stray magnetic field, frequency hysteresis, eddy currents. etc. They are especially useful in measuring very high pressures. They can also be used as leakage indicators or "ground detectors," since they carry no appreciable current and so do not introduce what is virtually a parallel leakage.

The electrostatic instrument can, by means of suitable additions, be used as an ammeter or a wattmater. The National Physical Laboratory uses an electrostatic wattmeter for standardisation work.

Supply Meters

These meters can be classified under three headings—Electrolytic meters, Motor meters, Clock meters. The first can only be used on D.C. circuits unless it is fitted with a transformer and full wave rectifier unit, when it can be used on A.C. circuits. The others can be used on either D.C. or A.C. circuits, depending on their construction. Supply meters used on D.C. circuits can be either watt-hour or ampere-hour meters. The registrations of the ampere-hour meter can be converted into watt-hours by multiplying by the voltage of the circuit, which is assumed constant. The meters are generally calibrated to read direct in kilowatt-hours. This type of meter cannot be used on A.C. owing to the question of power factor. It should be noted that the ampere-hour meter is a

quantity meter and the kilowatt-hour meter is an energy meter and is more important to the engineer since it takes into account the pressure at which the quantity was consumed. This gives a measure of the charge which should be made for the service. Since the pressure on any supply system only varies within a few per cent of the stated figure, it is usual to employ a simple ampere-hour meter that is calibrated in kilowatt-hours. This instrument has the advantages of simplicity, cheapness and low power consumption. A true watt-hour meter is usually used for power work, on A.C. circuits when the power factor varies, and on D.C. circuits where large equipment is used.

Electrolytic Meters

The readings of this meter are proportional to the weight of metal deposited, or of gas liberated, from an electrolytic solution. That is to say the readings are proportional to the number of ampere-hours passing through the meter. This meter is cheap, simple, and accurate on small loads, it is unaffected by stray magnetic fields, and as there are no moving parts, there is no frictional loss. Its disadvantages are a 1 to 2 volts drop across the terminals, and being made mostly of glass it is fragile; it also requires constant refilling and resetting. The two types most commonly used are the Bastion and Wright meters.

Motor Meters

These can be used on either D.C. or A.C. circuits. In this type the moving system revolves continuously, the speed of revolution is proportional to the current in the circuit, in an ampere-hour meter and to the power in a watt-hour meter. The number of revolutions in a given time is propertional to the quantity of electricity supplied in the ampere-hour meter and to the energy supplied in the watt-hour meter. The number of revolutions made by the spindle of the meter is recorded by a counting mechanism.

The speed of the rotating system is controlled by a permanent magnet which induces a current in a disc connected to the rotating system; this produces a retarding torque which is proportional to the speed of the rotating system. When the driving torque balances the retarding torque, the system attains a steady speed. Motor meters are subject to two principal errors, friction and braking. The friction error is the most important, since it operates continuously and affects the speed of the rotor, for any given value of the current. Static friction may even prevent the meter from starting on small loads, or if it starts, to register low. This can be compensated for. The frictional torque when the meter is running merely adds to the braking torque and is not very important in some meters, but in the mercury motor type it is proportional to the square of the speed and must be compensated for. The rotary system must be as light as possible in order to reduce the load on the bearings and hence the friction. The error due to braking is due to variation in strength of the brake magnet, and the increase in resistance of the disc due to a rise in temperature. Many devices are used to overcome this error.

There are two classes of motor meters for D.C. circuits—the mercury motor meter and the commutator motor meter. The main difference between these two types is in the method of leading the current into the armature. In the first type the armature is a thin disc of metal rotating in a bath of mercury, the mercury serving as contacts to lead the current in and out of the disc, the commutator doing this in the second type. The mercury type of meter is much more commonly used as house service meters than the commutator type. It has the advantages of simple construction, small voltage drop across the terminals, can carry larger currents without shunting, and smaller starting friction. The commutator motor meter can be used on D.C. circuits but not the mercury type. The principles of operation are essentially the same as those of the dynamometer watt-meter. The induction type of meter is generally used for A.C. energy measurements. It has many advantages over the commutator type. The principle of operation is almost exactly the same as that of the induction wattmeter. The construction of this instrument is in general the same as the wattmeter except the spring and pointer are replaced by a brake magnet and a recording mechanism. The accuracy of this instrument depends on making the following adjustments: the pressure flux to lag 90 degrees or slightly more behind the line voltage, "full load" adjustment and low load adjustment.

Clock Meters

The Aron "clock" meter is the most important of this type. It is unaffected by external fields and is practically free from wave-form and frequency errors, especially when the pressure coil is made as near as possible non-inductive. The meter registers accurately on very low loads. It can be used on either A.C. or D.C. It is not used as a house service meter owing to cost and complicated construction. It consists essentially of two identical pendulums (Fig. XII. 16) kept in constant oscillation by means of clockwork, electrically wound. At the bottom end of the pendulums are two flat coils connected in series and with a high resistance across the line. They carry current proportional to the low voltage. if this circuit is non-inductive and the resistance does not vary with temperature. Beneath each pendulum a current coil is fixed, these coils being connected in series with the line and wound so that the fields are in opposite directions. When no line current is flowing, the pendulums swing at the same rate, but if a current flows through the current coils, the speed of one pendulum is increased while that of the other is decreased. In short, the meter is in effect two clocks, one of which runs faster and the other slower when a current flows in the line. The counting mechanism is so arranged as to register only the difference in the number of swings of the two

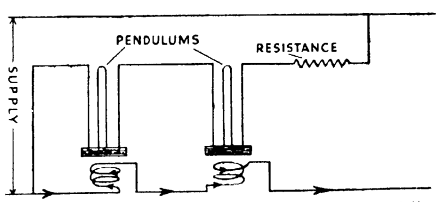


Fig. XII. 16. Diagram of Aron "Clock" meter.

pendulums, which is proportional to the current flowing, and this is done by differential gearing. Since it is practically impossible to get two pendulums having the same natural periods, the direction of the current in the pendulum coils is automatically reversed every 10 minutes, and arrangement is also made to prevent the meter from reading backwards when this is done by having two alternative trains of driving wheels, so that the drive from the differential gear can be thrown over at the same time as the direction of the current is changed. This instrument will read true watt hours on D.C. or A.C. of any wave-form or frequency.

There are many other important instruments that should be described but space does not permit. The reader who requires further information on the instruments described above, is referred to the standard referencee books on the subject.

CHAPTER XIII

FLUID

Fluids comprise both liquids and gases and fluid measurement deals with the methods and instruments employed in measuring weights or volumes or rates of flow of both these substances. Liquids and gases have different properties, and so it is convenient to deal with their measurement separately, although in certain cases the same principle may be used for the measurement of either. Different types of instrument are required, depending upon whether the fluid is at rest, or in continuous motion.

Units of Measurement

Volume. Fluids may be measured by volume, the unit being the cubic foot in the British system, or the millilitre in the metric system. A more common British unit is the gallon, which is the volume of 10 pounds of water weighed in air at 62° F. When gases are measured by volume the temperature and pressure at which the measurement is made must be stated, since the volume of a given weight of gas changes considerably with change of either of these factors.

Weight. Measurement by weight is convenient for either liquids or gases and involves no correction for temperature or pressure.

Measurement of a Liquid at Rest

A liquid at rest is usually measured by a standard vessel, of such a size that when it is filled to a given mark it contains a known quantity of liquid, or the vessel may have a series of graduations each indicating the quantity of liquid required to fill it to that mark.

Measures. The common two-gallon petrol can is an example of this type of measure as is also the pint glass and the quart bottle. In scientific work more precise instruments are required. The pipette consists of a narrow glass tube, tapered at the lower end, with a bulb blown in the centre of its length. A mark is engraved on the tube above the bulb so that, when the liquid is drawn up to this point, the pipette holds a known amount at a given temperature.

The standard flask is used for larger quantities. When filled to a mark on its neck the flask contains a known quantity of liquid. The neck is made narrow so that a slight error in filling will not cause a big error in volume.

Graduated Vessels. Standard measures will only measure one standard quantity and, where other quantities have to be measured, vessels carrying a number of graduations are convenient. On a large scale, these take the form of tanks fitted with gauge glasses or dipsticks to show the level of the liquid. These can be calibrated to read either the volume of the tank up to that level or, for a specified liquid, the weight.

Precise measurement of small quantities can be carried out with a measuring cylinder or a burette. The former is a glass cylinder of 1 in. to 2 in. diameter which stands on a base and has a series of graduations up the side, each showing the volume of liquid which the cylinder holds when filled to that mark. The burette is a long glass tube about $\frac{1}{2}$ in.

diameter fitted with a tap at its lower end. It is graduated up the side so that, by opening the tap, any required quantity of liquid can be measured out.

Measurement of Liquids in Motion

Low Pressure Meters. This type of meter is convenient for measureing liquids which are not under pressure, such as waste water. One type consists of two tanks, mounted on trunnions so that the tank overbalances when it contains a certain quantity of liquid. A chute directs the flow into one tank and, when the fixed quantity has flowed into it, the tank tips and discharges its contents into the outlet. The tipping of the tank tips the chute so that the other tank starts filling and the process continues. A counter automatically records each discharge and can be calibrated to read the quantity in gallons direct.

Positive Meters. The positive meter is a small hydraulic motor either of the reciprocating piston or rotary piston type. All the water to be measured passes through the cylinder of the engine and the volume passed per stroke will be equal to the piston displacement. By counting the number of piston movements by a suitable mechanism the meter can be calibrated to read direct the quantity of liquid passing through. Note that the flow through the meter is divided into uniform isolated quantities, but by using double-acting pistons or a multiple cylinder arrangement, a continuous flow is maintained.

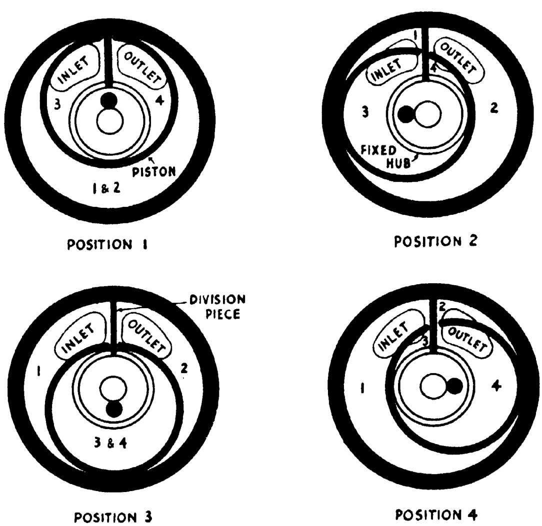


Fig. XIII. 1. Rotary piston meter.

Position 1. Water from inlet port enters space 3 inside the piston, forcing it down and round. Spaces 1 and 2 are neutral and water is discharged from space 4.
Position 2. Spaces 1 and 3 are receiving water. Spaces 2 and 4 are discharging.
Position 3. Spaces 3 and 4 inside piston are now neutral. Space 1 is receiving water and space 2 is discharging.
Position 4. Spaces 1 and 3 are receiving water. Spaces 2 and 4 are discharging.

The Empire meter is an example of the rotary piston type. Fig. XIII. 1 shows the method of action. The hollow piston is free to slide along the division piece and carries a pin at its centre which slides round a groove in the fixed hub as the piston oscillates inside the cylinder. The circular motion of the pin is transmitted to the recording gear. In position 1 the piston is over the inlet port and water enters the inside of the piston causing it to slide down the division piece and move round the hub at the same time displacing water to the outlet port which is now open to the cylinder as in position 2. The inlet water is now able to press both on the inside of the piston and on the inlet side of the cylinder and the piston is forced round to position 3. At this point the inside of the piston is cut off from the inlet port, and the pressure of water on the inlet side of the cylinder forces the piston on. Finally, the inside of the piston is brought over the outlet port thus allowing it to return to position 1 for the start of a new cycle.

The Imperial Positive Meter is a typical example of the reciprocating piston meter. It comprises three single-acting vertical cylinders grouped symmetrically about a central hemispherical gun-metal distributing valve on a hemispherical vulcanite seating. The pistons are connected to the valve, so as to give it a rotary oscillating motion. The inlet pressure acts on top of all three pistons. The underside of each piston is connected, in turn, to the outlet by the motion of the valve allowing it to be forced down by the pressure on top whilst at the same time water is admitted beneath the other two pistons as they rise.

Inferential Meters. In the inferential meter the flow passes through a small turbine impellor or fan, driving it round, and operating the recording mechanism. The liquid is not measured in definite quantities as in the positive meter but the flow is inferred from the number of

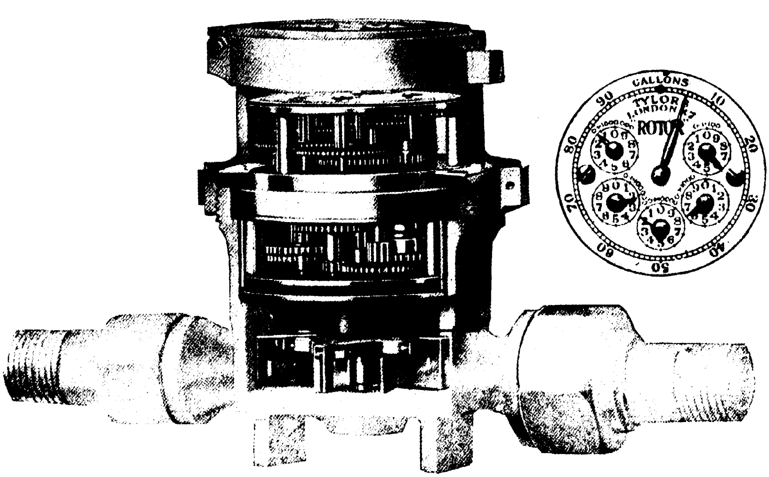


Fig. XIII. 2. Tylor's inferential meter. The quantity of liquid passing through the meter is inferred from the number of revolutions of the fan.

revolutions of the fan. For this reason the meter must be calibrated by passing known quantities through it. It is light, cheap and small, but its accuracy decreases for small rates of flow until finally, for very slow flows, the force on the fan becomes insufficient to actuate the recording mechanism. Also the runner tends to go on rotating after the flow ceases, causing the meter to record too large a quantity. This type is therefore only suitable for measuring continuous flow at good speed.

Tylor's inferential meter is of this type. The mode of action can be seen from the illustration (Fig. XIII. 2) where the nickel fan can be clearly seen. Another version is the "Fullflow" meter which is designed to measure large flows with a minimum loss of head. The liquid passes through the meter in a straight line, driving a light fan as it flows (Fig. XIII. 3).

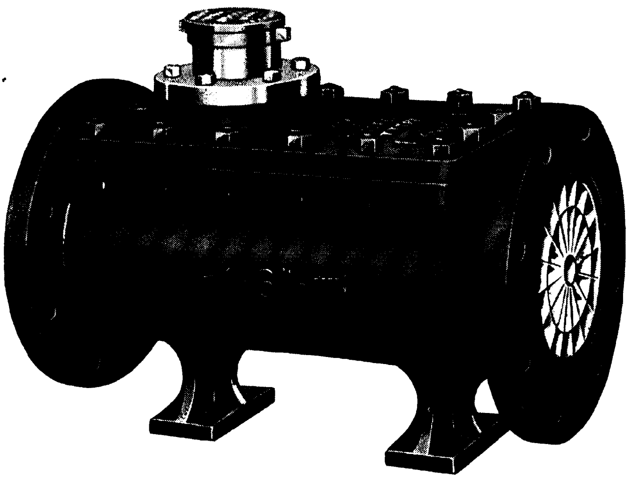


Fig. XIII. 3. "Fullflow" meter· An inferential meter specially designed for low loss of head.

Sightflow Meter. This consists of a vertical transparent tube, having a conical bore and set with its wide end at the top, in which there is a free top-shaped float. If there is no flow the float rests at the bottom of the tube. When flow begins the float must rise towards the wider end of the tube. The position of the float in the tube can be read on a scale and is a measure of the rate of flow in the tube. The scale is calibrated to read quantity directly and is linear. Advantages claimed for this meter are great accuracy and the fact that any fouling of the meter can be detected immediately. Special arrangements can be made for metering opaque fluids or for fitting remote reading or recording instruments.

Venturi Meter. The action of this meter depends on the fact that the total energy of a continuous flow of water remains constant and so

when a constriction is formed in a pipe the pressure must fall since the velocity and therefore the kinetic energy of the liquid has increased. From measurement of the difference of pressure between the liquid in the reduced section and that in the normal section of the pipe, the rate of flow can be calculated. The illustration (Fig. XIII. 4) shows a typical

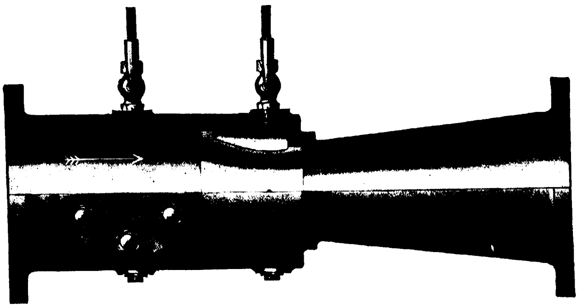


Fig. XIII.4. Venturi tube (short pattern). The pressure tapping at the throat is taken from an annular chamber connecting to the throat at a number of points round the circumference.

short pattern venturi meter, partly in section. The pressure difference between the two tappings is measured by any type of manometer which may be calibrated to read the rate of flow direct or made to operate a graphical recorder.

Orifice Meters. If a thin orifice plate is placed in a pipe line with a diameter of opening less than that of the pipe the liquid will pass through the opening in the form of a jet. The velocity immediately beyond the plate will be higher than upstream of the plate and therefore, as in the venturi meter there will be a pressure difference between the two sides of the plate. This difference is measured by a manometer and can be used to calculate the rate of flow in the pipe. The illustration (Fig. XIII. 5) shows the method of installing such an orifice plate which, in this case, is mounted in a carrier ring complete with pressure tappings on the upstream and downstream sides. The carrier is placed between the flanges of the pipes and is automatically located by the bolts. Flow can be read direct from a special manometer connected to the pressure tappings.

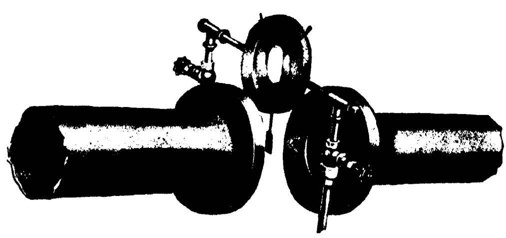


Fig. XIII. 5. Installing a carrier ring type orifice plate. Pressure tappings are taken from annular grooves, on the upstream and downstream side of the orifice, and are integral with the carrier.

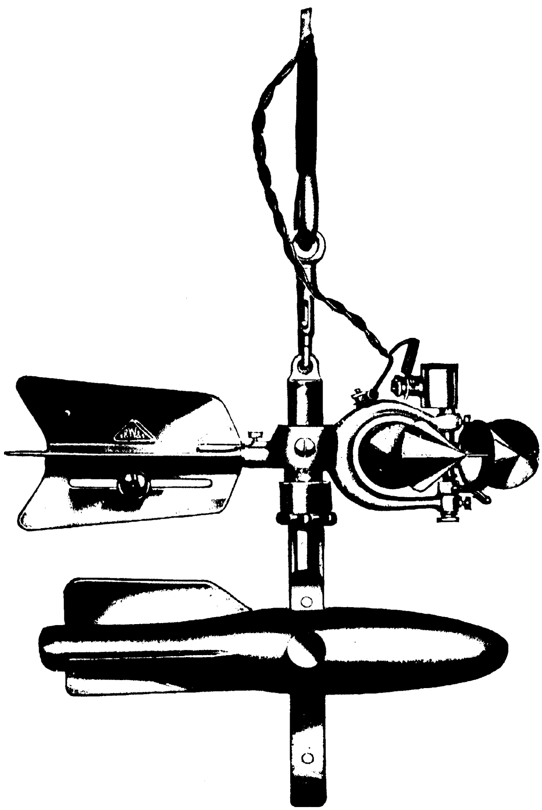


Fig. XIII. 6. Current meter. Speed of the bucket wheel is proportional to the speed of the current. An electric circuit is broken at each revolution enabling the speed of the wheel to be found.

Current Meters. The inferential type of meter can be used to measure the speed of flow of rivers and open channels. The meter consists of a propeller or bucket wheel (Fig. XIII. 6) with a guide vane to keep it head on into the current and a sinker to maintain its axis horizontal. The rotation of the bucket wheel operates a counter, usually electrically, by breaking an electrical circuit at each revolution, and from the counter reading the speed of flow can be found. Such instruments will record velocities from about 6 inches per second.

Weirs and Notches. A weir consists of a barrier across a channel or river over which the water must flow. If an opening is cut in the barrier it is termed a notch and if the opening is V-shaped it is called a V-notch. In both cases the quantity of water flowing over a weir or notch is a function of the height of the upstream water level above the top of the weir or the apex of the V-notch. By the simple process of measuring the height of upstream water level above the bottom sill of the notch or weir the quantity of water flowing in the channel can be measured. To record this level a float is used in a float-well communicating with the channel upstream of the weir and the level of the float can be made to operate a recorder showing the rate of flow.

Where large fluctuations of flow may occur a V-notch is used to measure the small flows, while the top of the notch is enlarged to form a rectangular weir, to handle large flows, the recording mechanism automatically correcting for the change, and reading the rate of flow direct

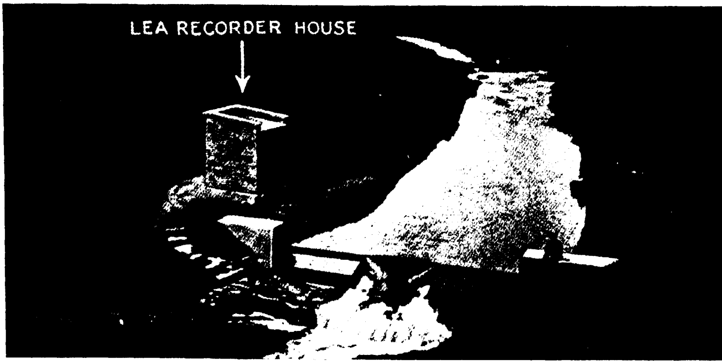


Fig. XIII. 7. Compound obtuse-angled V-notch and rectangular weir. Installation measuring the flow of a river in North Wales. Capacity 250,000,000 gallons per day.

for any water level. The illustration (Fig. XIII. 7) shows such a compound V-notch and rectangular weir used to measure the flow of a river.

Standing Wave Flume. The water level below a weir is considerably below that upstream. This fall in level cannot always be arranged. For such cases the Standing Wave Flume is a convenient method of measurement as it operates with a very small loss of head. It consists of an open channel with a large constriction in it (see Fig. XIII. 8) through which the water flows very swiftly, the water level in the throat falling very considerably below the upstream level. When this fast flowing shallow stream of water comes out of the constriction it is slowed up and the water level rises rapidly in the form of a standing wave. The rate of flow through the constriction is a function of the height of the upstream water level above the bottom of the constriction and the measurement of flow

Fig. XIII. 8. Standing wave flume. Installation at Manchester Waterworks. Capacity 35,000,000 gallons per day. Note V-shaped standing wave in the foreground.

becomes the simple operation of measuring the upstream water level. These flumes are easy to construct and operate, causing little loss of head and offering no obstruction to floating or suspended matter, a point of importance in river or sewage measurement. The recording gear is similar to that used for weirs and notches.

Measurement of Gases

The legal standard of gas measurement is the cubic foot bottle which is specified as holding 62.321 pounds of water when weighed in air at 62° F. It should be noted that the weight of gas occupying a given volume will depend on the temperature and pressure which should be recorded for all volume measurements. Quantities of gas measured under different conditions can be compared by referring them to Standard Temperature and Pressure (S.T.P.), that is to say by converting the actual volume measured to the volume the gas would occupy at a temperature of 0° C. and a barometric pressure equivalent to 76 cm. of mercury.

Wet Type Coal Gas or Air Meter. This consists of a drum revolving in a cylindrical casing which is rather more than half filled with water. The drum is divided into compartments by partitions. One end of each partition is always below the water surface while at the other end there is an opening between the compartment and the outer casing. Gas enters through a central pipe and leaves by the outer casing as shown in the diagram (Fig. XIII. 9). Compartments B and C are full of gas, C is delivering to the outlet, B is about to cut off from the inlet and A is just beginning to receive gas. As the gas in C is drawn away to the burners the pressure of incoming gas causes the drum to rotate and brings B into communication with the outlet. Thus each compartment fills and empties in turn as the drum rotates and a revolution counter attached to the drum can be arranged to read the volume delivered direct. The position of the water level in the drum is very important since it affects the amount of gas delivered to each compartment. Various devices have been developed to maintain the level constant; large station meters are fitted with syphon overflows. This type of meter is accurate but is bulky and the use of water introduces complications due to evaporation, freezing and the maintenance of water level. As a result the dry gas meter is more popular for household use.

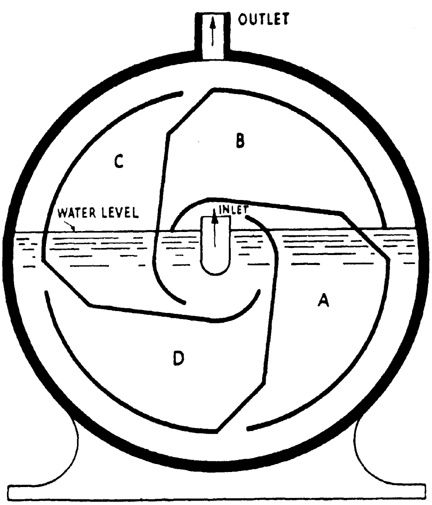


Fig. XIII. 9. Wet-type gas meter.

Dry Type Coal Gas or Air Meter. This type of meter is, in essence, a small double acting reciprocating engine with diaphragms instead of pistons and having the ordinary type of slide valve mechanism to regulate the admission of gas to either side of the diaphragm. The usual meter consists of a rectangular box divided into two compartments by a solid partition. Each compartment is divided in two by a diaphragm and is fitted with a slide valve mechanism so that the whole meter comprises two double-acting cylinders. The diaphragms each consist of a metal plate with a flexible leather gastight connection to the sides of the compartment. Guides are provided to make the diaphragm move parallel to itself. A slide valve is actuated by the motion of the diaphragm. As the gas is drawn away to the burners from one side of the diaphragm the pressure of the incoming gas on the other side pushes the diaphragm over until, as it reaches the end of its travel, the slide valve comes into action to admit gas to the empty chamber and connect the full chamber to the outlet. The purpose of having two diaphragms in separate compartments is to maintain a steady flow of gas by arranging that when one diaphragm is at the end of its stroke the other is at the centre. A counter connected to the slide valve mechanism records the number of times the diaphragms fill and empty their compartments and is usually

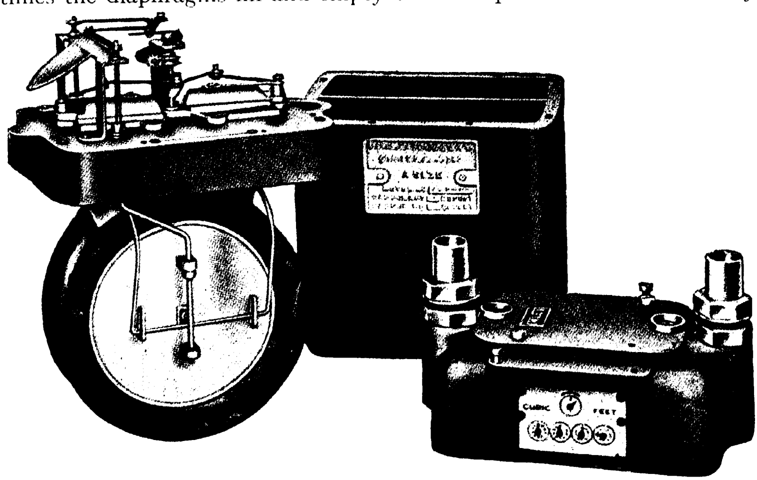


Fig. XIII. 10. Dry-type gas meter. Iron-arc meter in sections.

made to read in cubic feet. The diaphragm and slide valves can be seen in the illustration (Fig. XIII. 10) which shows the components of a typical gas meter.

Orifice Meters. The orifice meter described for liquids can also be used for measuring the rate of flow of gases. The pressure difference will not be as great as for liquids and a sensitive manometer is required. A U-tube having one leg vertical and the other inclined and filled with water or oil is suitable, since the liquid will move a long distance in the inclined leg for a small change of pressure. The rate of flow is a function

of the square root of the pressure difference at the orifice and this causes the graduations of a scale reading quantity to be very close together at the lower end, but an evenly-divided scale can be obtained by curving the inclined leg so that it becomes more nearly vertical at its upper end.

Shunt Gas Meter. The pressure difference caused by an orifice plate in the main pipe is used to force a certain proportion of the gas flow through a by-pass circuit where it is directed by nozzles on to the blades of a fan. The number of revolutions of the fan is an indication of the volume of gas passing in the main. The mode of action can be seen from Fig. XIII. 11. The fan actuates a counter mechanism through a magnetic drive which makes a gland unnecessary, thus ensuring no leakage of gas from the fan chamber. Such meters have an accuracy of plus or minus 2 per cent and will handle flows from as low as 400 cu. ft. per hour.

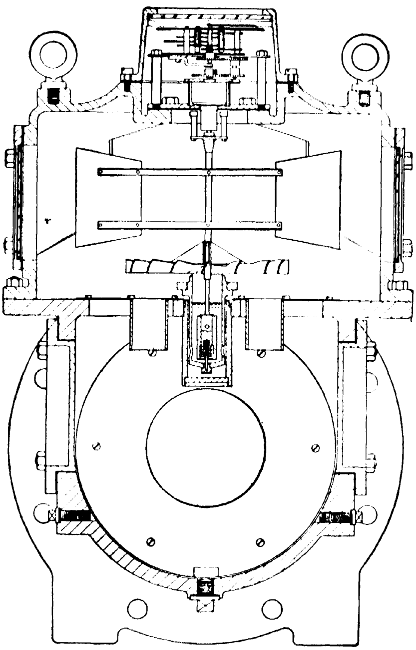


Fig. XIII. 11. Shunt gas meter. Sectional drawing showing the orifice which diverts a portion of the gas through a fan type inferential meter.

Gate Type Air Flow Indicator. A light hinged gate is pivoted eccentrically in a circular chamber and controlled by a spring. As the rate of air flow increases the gate opens and a pointer attached to it moves over a scale calibrated to read the rate of flow; the instrument is robust and suitable for use with pneumatic tools.

Anemometer. This instrument is used for measuring wind velocity and the speed of air currents, for example in ventilating ducts. The flow of air rotates a light mica fan geared to a counting mechanism which reads the number of feet of air passing through the fan. The air speed can be found by taking the reading over a given time.

Pitot Tube. For high velocity air, gas or water currents a pitot tube gives good results. It consists of a bent tube terminating in a small orifice pointing upstream. An outer tube surrounding it has a number of small holes in its wall but is not open in the direction of flow. The centre tube records the pressure due to the impact of fluid on the orifice and the outer tube records the mean static pressure. The two tubes are connected to a manometer and the velocity of flow can be calculated from the pressure difference recorded (see air-speed indicator page 178).

CHAPTER XIV

PRESSURE

The pressure exerted by a fluid is defined as the force acting on unit area, and expressed as pounds per sq. in., or kilograms per sq. cm. Other units also are used, high pressures being given in terms of atmospheres, and low pressures as a "head" of liquid such as inches of water, or mm. of mercury. It is usually understood that pressures are measured as above or below that of the atmosphere, thus a statement that the oil pressure in an engine is 40 lb. per sq. in. is understood to mean that it is so much above atmospheric pressure. Absolute pressures are usually referred to specifically as such.

U Tube (Fig. XIV. 1). This simple device is used extensively to determine gas pressures in the lower ranges. The most elementary form is a bent glass tube, half-filled with liquid, and fitted with a scale. Pressure applied to one limb causes the liquid to rise in the other until equilibrium is reached, when the "head" can be measured. Unfortunately in this simple form only half the total change occurs in either limb, but this can be overcome by using a vessel of comparatively large area on one side, when most of the movement will take place in the other. The sensitivity may be further increased by inclining the tube, and the pressure scale may be graded by using a curved one. The most useful liquids for U-tubes are water and mercury, although greater sensitivity is obtained with light oils, and intermediate calibrations with some heavy organic liquids. Viscous or volatile liquids are definitely unsuitable. Measurements are usually made with one limb open to the atmosphere, but if the two limbs are connected to separate sources of pressure the gauge shows the difference between them. In this way it is frequently used to measure flows in pipes or ducts; the pressure difference being produced by a restriction or orifice of known characteristics.

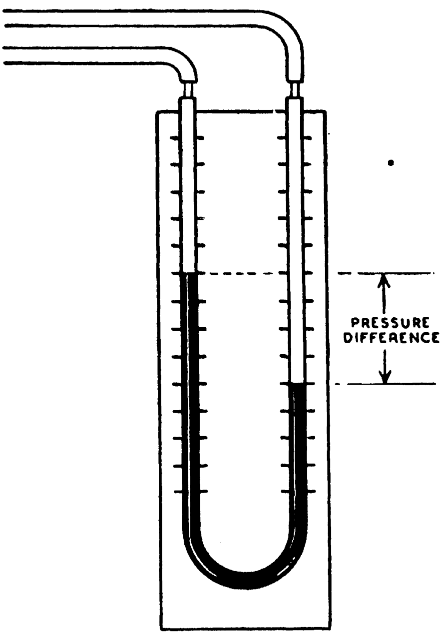


Fig. XIV. 1. Liquid-filled U tube.

The industrial applications of U-tubes are innumerable. Sometimes they are seen in a very simple form, whilst for some purposes the design becomes so involved that the elementary principle may be difficult to recognize. When it is required to show the pressure by a pointer and scale, or to record it on a chart, this can be done by having a float on the liquid in one limb linked to a suitable mechanism.

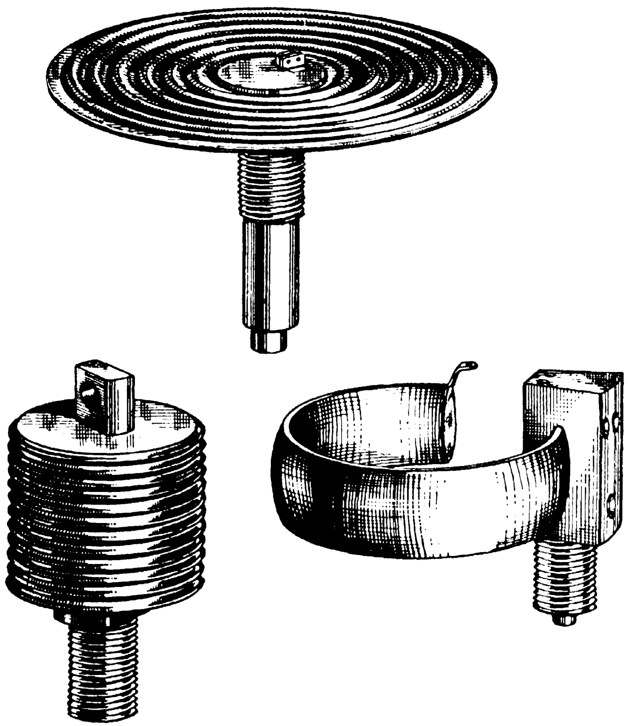


Fig. XIV. 2. Capsule, metal bellows, and Bourdon tube.

This type of gauge can be made to measure pressures down to 0.01 in. water, although at these low values the accuracy may be limited by surface tension effects. The maximum pressure is determined by the length of column it is convenient to read. If this is assumed to be six feet, then with mercury filling this corresponds to about 35 lb. per sq. in.

Diaphragm Gauge. This sensitive element is a disc of thin material, which being held at the periphery, is deflected by a difference between the pressures on the two sides. Diaphragms are commonly made of corrugated metal, but fabric such as oil silk has been used for low pressures. Suitable metals include nickel-silver, phosphor-bronze, beryllium-copper, and steel. Diaphragms are often assembled in pairs to form a capsule, and there is considerable scope for variation in the pressure

characteristics by the suitable selection of material, and of the form of corrugation. The useful movements of a diaphragm are rather small, and generally require magnification, so the centre is linked to a rack and pinion mechanism, and this, or some similar device, turns a pointer. This type of gauge is rather liable to damage by excessive overload so the deflection has to be limited by stops, but otherwise it is very serviceable, and has wide applications in industry, and aeronautical science. The useful pressure range is wide. Diaphragm gauges can be made to measure fractions of an inch water gauge, or to withstand pressures of many pounds per sq. in.

Metal Bellows (Fig. XIV. 2). These can be built up from a number of capsules, but more commonly are formed from a thin walled tube by hydraulic pressure, or a spinning process. They are generally used with higher pressures than are simple capsules, and they can give considerable movement, but their rigidity is nearly always augmented by a spring. They are generally used in pressure-operated control devices, but a few are employed successfully as pressure gauges. When bellows are built up from a number of diaphragms the same choice of metals is available, but when formed from tube the metal has to be capable of withstanding the severe cold-working which this process involves, and the choice is limited to fewer alloys. Flexibility can be increased by making the bellows with laminated walls.

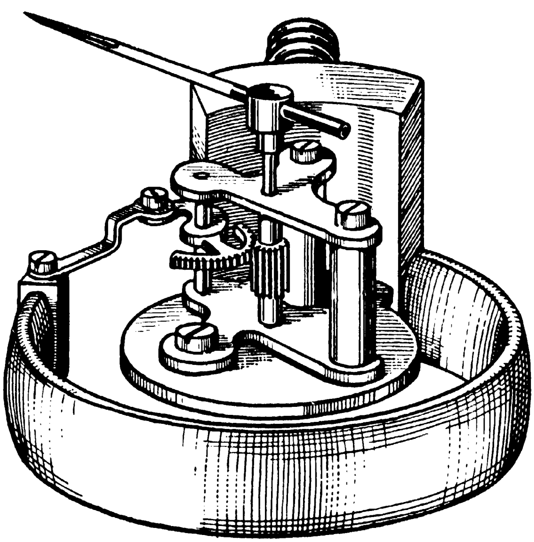


Fig. XIV. 3. Mechanism of Bourdon tube pressure gauge.

Bourdon Tube. This is the basis of most commercial gauges (Fig. XIV. 2 and 3. It consists of a curved tube of elliptical cross-section. Under the influence of internal pressure this tends to become straight, that is the radius of curvature increases, so that if one end is held firmly

the other moves in proportion to the pressure. The movements are quite small, and so some form of rack-and-pinion mechanism is necessary to work a pointer. There is considerable difference of opinion as to the best form for the elliptical tube, and as the theoretical treatment is very complex, the ultimate shape is usually based on experience. Bourdon tubes are rather liable to distortion by overload if attempts are made to use a large movement, so commercial practice is to allow a generous margin of safety, and the result is an extremely robust, and economically produced instrument. An overload stop may be found on the more precise instruments, and sometimes stops are fitted at intervals along the bourdon tube to modify the scale shape. These gauges can be designed to measure pressures between 5 and 20,000 lb. per sq. in., although special difficulties attend the construction of instruments with extreme ranges.

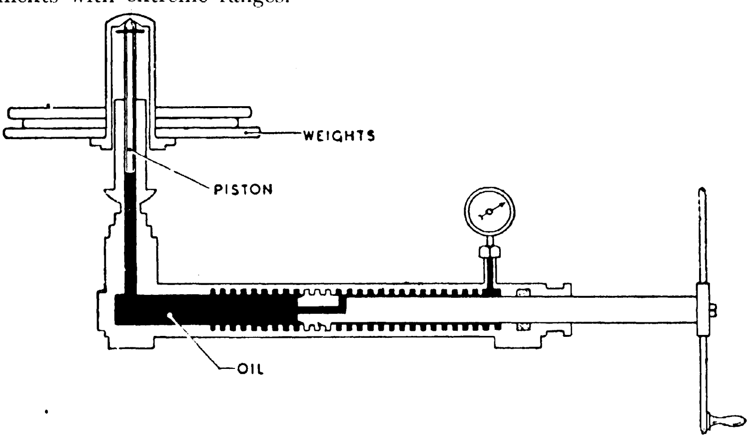


Fig. XIV. 4. Piston gauge.

Piston Gauge (Fig. XIV. 4). This instrument has a piston of known area working in a cylinder so that fluid pressure applied to one end can be opposed by measurable forces at the other. It is usually arranged so that the piston moves up and down in a vertical cylinder in which it is an accurate fit, and oil pressure is applied below it. Weights are then suspended from the top of the piston by a carrier, and being in the form of rings: hang around the cylinder. Alternatively the force can be applied through a lever, and other elaborations become necessary when dealing with very high pressures. Friction between piston and cylinder must be avoided when taking a reading and this is done by causing the piston to turn, which is quite easy with the arrangement described above, for the weights can be spun by hand, and carry the piston with them.

The ranges of these gauges are limited by practical considerations of the size of the piston, and of the weight needed to load it. Pistons with areas between 0.1 and 0.01 sq. in. are usual, and can carry weights up to 100 lb., which in the case of the smaller size corresponds to a pressure of 10,000 lb. per sq. in. The larger size can be used for pressures down

to 10 lb. per sq. in. if manipulated with care. These instruments are generally employed as primary standards for the calibration of other gauges, and they do in fact lend themselves to the determination of definite values rather than the measurement of unknown ones. That they are not readily applicable to the standardisation of low pressures does not matter, for U tubes containing either water or mercury provide primary standards in this range.

Gauges for Special Purposes

Very High Pressures. The measurement of very high pressures calls for special apparatus although the bourdon tube can be used up to 30,000 lb. per sq. in., or 2,000 atmospheres, if particular care is taken in the construction of the gauge. Other principles are employed for still higher values. There are methods depending on the change in volume of a vessel when under pressure, or on the determination of the stress in its walls, and gauges have been made which utilise the change in electrical resistance with pressure which most metals show to some extent.

The high pressures generated by explosions present unique problems, and if the build-up of the pressure is to be followed then apparatus like that described in the next paragraph is required, but often it is necessary to know only the maximum value, and this can be found in other ways. One practical scheme is to use a piston of known area to press a steel ball into a metal block, and to determine the pressure from the size of the resulting "Brinell" indent, and the hardness of the metal block. This apparatus can be calibrated without the application of fluid pressure; it is simple and can be used for the highest pressures. The standard comparative test for explosives is known as the Trauzl test. The explosive is detonated in a cavity in a lead block under standard conditions and the resulting distension provides a comparison of the explosive effect.

Pulsating Pressures and Engine Indicators. These instruments commonly make a record of the pressure against either a time base or crankshaft position in the case of engine indicators. These were first introduced to study the pressure cycle in slow-moving steam engines, and the principle of such an instrument is depicted in Fig. XIV. 5. The engine pressure is fed to a cylinder with a piston whose movements are controlled by a calibrating spring, and recorded on a chart by the pen to which it is linked. The chart is wrapped round a drum and this is caused to oscillate in synchronism with the engine piston by a cord attached to the link-work, and kept taut by a spiral spring inside the chart drum. Thus the pen makes a cyclic diagram on the chart in which cylinder pressure is graphed against crankshaft position. The same principle can be applied to modern high-speed engines, but much refinement of design is necessary to ensure that the record is a true picture of the actual conditions in the engine. The moment of inertia of all moving parts has to be reduced, and also the extent of their travel; in fact the apparatus may be made so small that the diagrams can only be studied after optical magnification. It is often desirable to make the trace on a continuously moving medium, using an electrical signal to correlate the record with crankshaft position.

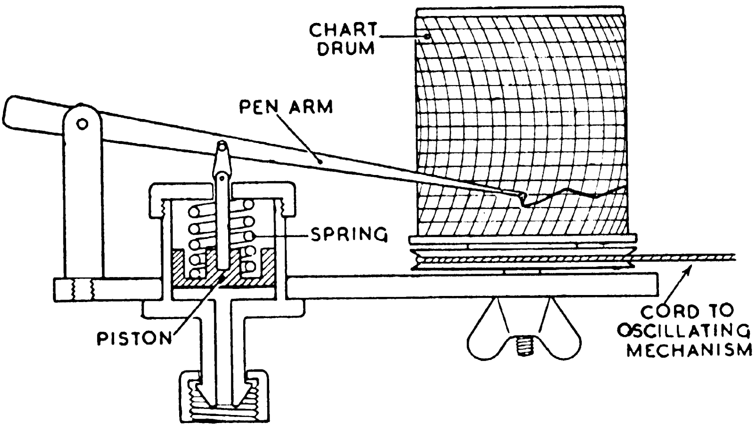


Fig. XIV. 5. Engine indicator.

The cathode ray oscillograph is a very effective tool for the study of rapidly-changing phenomena, and can follow the most transient pressures when used in conjunction with a "pick-up" to convert the pressure changes into electrical impulses. It has been used for work on engines with the highest speeds, and on explosive effects.

Micro-manometers. This name is applied to instruments which can measure small differences of pressure not far removed from atmospheric, and they find particular application in the study of problems associated with ventilation and in aeronautical research. The liquid-filled U-tube may be used if the surface levels can be determined with sufficient accuracy, and in one type associated with the name of Threlfall this is done with a micrometer. The limbs are of large diameter, and the micrometer is mounted over one of them. The screw ends in a point, and the surface is located by turning the screw until the point just touches the liquid when this seems to jump up and adhere to it. In this way pressures can be measured to within 0.002 in. water gauge by careful manipulation. Another type known as the Chattock gauge measures the head by tilting the tube until there is no displacement of liquid. The glass U-tube is mounted on a frame which can be tilted by a micrometer screw, and the limbs are more widely spaced than usual. One is continued upwards into, and concentric with a central vessel to which the other limb is connected. This central vessel is filled with water and oil, the surface of separation in the inner tube being viewed through a microscope with cross wires in the eye-piece. Pressures are therefore read off on the micrometer screw when the frame has been tilted to bring the surface of separation back to the datum line provided by the microscope.

A thin metal diaphragm can also respond to these small pressure differences but the deflections may be so minute that mechanical magnification is quite out of the question. However, they can be measured by a microscope, or better still with the help of an optical lever. This

comprises a pivoted mirror which is rocked as the diaphragm moves, and so deflects a beam of light projected on to a scale, and great magnifications can be obtained in this way. Another way of locating the diaphragm is by means of a micrometer which completes an electric circuit as soon as it touches it. If a sensitive galvanometer is used to detect the current, measurements can be made to within 0.00005 in. Diaphragm gauges have certain advantages over fluid types for they are instantaneous in response and free from errors due to drainage or surface tension. However, they do need calibration against a primary standard.

Boost Gauges. These are also called manifold pressure gauges for their purpose is to measure the pressure of the fuel mixture in the intake manifold of internal combustion engines. They are calibrated in terms of absolute pressure although sometimes the zero mark on the scale may correspond to some standard atmosphere, and the instrument is calibrated to measure both above and below this value. Boost gauges usually comprise an evacuated capsule or metal bellows, and the unknown pressure is applied externally. The capsule or bellows respond to the pressure difference between inside and outside, and since the pressure inside is zero, the movements are dependent on the absolute value.

Vacuum Gauges

Vacuum pressures are expressed in mm. of mercury above theoretically perfect vacuum or zero pressure, and therefore are absolute values. The term vacuum actually covers a wide range of pressures which cannot be covered by any one type of instrument. Rough vacua, that is, pressures above 1.0 mm., can be read on a simple U-tube having one limb sealed off, and evacuated above the mercury, and refinements can be added to make lower pressures readable, but generally vacua down to 10^{-4} mm. are most conveniently determined by instruments based on Boyle's Law, or the compressability of gases. A typical example is the McLeod Gauge. Below 10^{-2} mm. other gauges can serve, but these depend on some other property of a gas such as its thermal conductivity or viscosity.

McLeod Gauge. A typical construction of this gauge is shown in Fig. XIV. 6. It consists of a bulb connected to the vacuum system by a side tube entering at the bottom, where it also joins a barometric tube filled with mercury, and connected by rubber tubing to a reservoir whose height can be altered. It is seen that the bulb ends in a tube of small bore sealed off at the top, and that the side tube has a loop arranged alongside this. To make a measurement the reservoir is lowered until the mercury is below the junction of the side tube and bulb, so that this is in connection with the rest of the apparatus, and therefore reaches the same pressure. The reservoir is then raised, and as the mercury also rises in the barometric tube it traps the gas in the bulb, and compresses it into the upper or bulb tube. The excess pressure needed to do this is shown by the difference in level of the mercury. The loop on the side tube is made of the same size as the bulb tube to prevent errors due to capillarity. The gauge can be used in two ways. Either the gas can be compressed into a given length of the bulb tube, and the vacuum calculated from the pressure required to

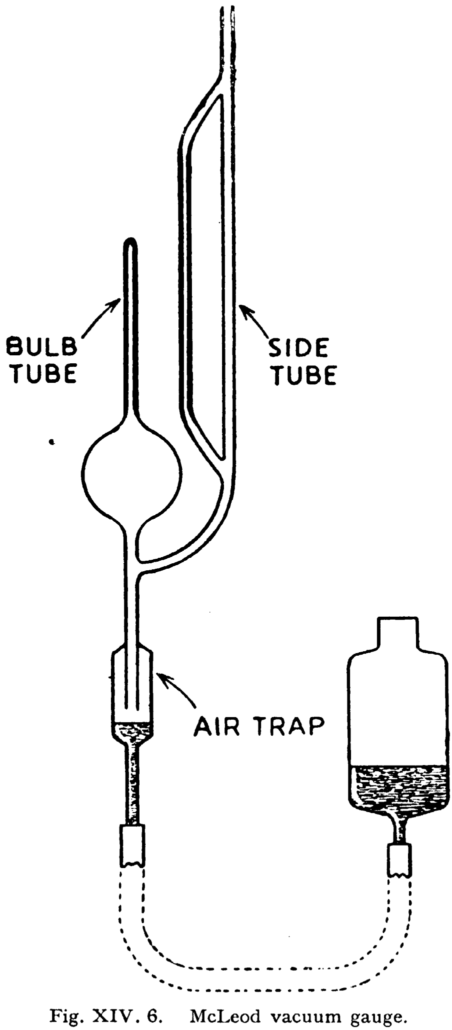


Fig. XIV. 6. McLeod vacuum gauge.

do this, or the mercury in the loop can be brought to some selected zero, opposite the closed end of the bulb tube, for example, and the level of the mercury in this tube read off against a calibrated scale. The first method gives a uniform scale of short range, whilst the second results in a scale which is more open at the lower pressures, and covers a wider range.

This gauge serves as a standard for calibrating other types of low-pressure gauges for its own calibration is calculated from the capacity of the bulb, and the bore of the bulb tube, and the relations of these two control the range of the instrument. For example, a bulb with a volume of 100 cc. having a tube of 1.2 mm. bore would permit pressures up to 0.1 mm. to be read by the second method on a tube 10 cm. long. In this form the McLeod gauge is slow in action and requires a measure of skill for its use, so various modified forms have appeared, most of which try to avoid the manipulation ef the mercury reservoir. They do so either by using pressure to control the mercury level, or by tilting the whole instrnment, but the fundamental principle remains unchanged. The gauge has the disadvantage that it contaminates the vacuum with mercury vapour unless this is trapped.

Thermal Conductivity Gauges. These are usually associated with the name of Pirani, and the most common arrangement consists of a length of platinum or tungsten wire sealed into a bulb, like a lamp, which is fused on to the vacuum system. If the wire is heated by an electric current the energy required to maintain it at a temperature of say

100° C. will depend largely on the rate at which heat is lost through the wire supports, and the surrounding gas. The latter will vary with pressure. The wire is connected electrically into a Wheatstone Bridge, and since its resistance changes with temperature, this bridge can be set so that it is balanced when the wire is at some particular temperature. The condition of balance is detected by a galvanometer and measurement is generally made by adjusting the current through the bridge until it is balanced, when the current is read off on an ammeter calibrated directly in mm. of mercury. The principle permits the construction of satisfactory commercial instruments, but unfortunately its calibration does depend on the gas involved, and it has to be calibrated against some standard such as the McLeod Gauge. It functions satisfactorily with pressures between 0.1 and 10^{-4} mm. mercury.

Ionisation Gauges. These are similar in form to a triode valve, and are sealed on to the vacuum system in the same way as the Pirani Gauge. The filament, or cathode, is heated by a current in the usual way, and when a positive potential is applied to the anode a current results. As the electrons forming this current pass through the gas, they collide with some of the molecules which become ionised, the resulting positive ions being attracted to the grid or "collector" which is charged negatively. Thus there flows in this circuit a small current whose magnitude depends on the pressure at low values, provided that other factors are kept constant. It can be used to measure pressures from 10^{-2} mm. mercury down to the lowest obtainable provided that instruments with adequate sensitivity are available to measure the ionisation currents. The actual calibration depends on the gas present, and its chief use is in the routine evacuation of such appliances as valves and X-ray tubes.

There are other gauges based on different principles. For example the Langmuir and Dushman molecular gauge, and the King Decrement gauge both depend on the change of gaseous viscosity with pressure, whilst Knudsen has devised instruments using radiation effects, but their field of use is rather limited to special applications.

CHAPTER XV

TEMPERATURE

Temperature Scales

Temperature is measured by measuring the change of any precisely measurable property of a body which has been observed to change when the body is made hotter or colder. For instance, if a glass bulb with a capillary tube sealed to it is filled with mercury to a suitable level in the tube, the height of the mercury level in the tube may be used to measure the temperature of the bulb, and, therefore, of any material in which the bulb is inserted. To set up a temperature scale with this thermometer, it is first immersed in melting ice, and the level of the mercury in the tube is marked when it is quite steady. The thermometer is then immersed in steam from boiling water, and the new level marked. The precautions for making this calibration accurately will be noticed later. These two levels are called the fixed points of the thermometer, and the interval between them the fundamental interval. For a centigrade scale (used internationally and for scientific work) the fundamental interval is divided into a hundred equal lengths and numbered 0° C. to 100° C., assuming the capillary to have a uniform bore. The division of the stem may be extended above and below the fundamental interval. For a Fahrenheit scale (used for British meteorological and clinical work) the fundamental interval is divided into 180 lengths and labelled 32° F. to 212° F. The difference between the Centigrade and Fahrenheit scales is merely a numerical one ; the simple formula :

$$\text{degrees Fahrenheit} = (\frac{9}{5} \times \text{degrees centigrade}) + 32$$

$$\text{or} \quad \text{degrees centigrade} = \frac{5}{9} \times (\text{degrees Fahrenheit} - 32)$$

converts from one to the other. The difference in temperature scale resulting from the choice of another expanding substance (e.g. alcohol or a gas), or of another thermometric property (e.g. the change in electrical resistance of a wire, is, however, a difference of a more radical nature, and no simple formula will convert mercury thermometer temperatures into, for instance, gas scale temperatures. Every thermometric property has its own temperature scale ; all these agree at the fixed points (since every thermometer is calibrated with this fundamental interval in the way described above) but at other temperatures the scales differ.

For theoretical reasons, the temperature scale adopted internationally as standard, is one measured by the expansion of a gas, and the fixed points are labelled 273.16° and 373.16°. This scale is variously called the perfect gas scale, the absolute, the thermodynamic, or the Kelvin scale, and is denoted by °A or °K. For accurate work it is desirable to calibrate the particular thermometer used against the absolute scale, and to do this without the very arduous process of using a gas thermometer, an international commission has published a number of accurately reproducible temperatures on the absolute scale, together with a specification of how to measure any intervening temperature. This scale is called the international temperature scale (°Int.).

The Choice of a Thermometer

By calibrating against the international scale we are free to use any thermometer without committing ourselves to the scale peculiar to the particular working substance chosen. We now review some of the considerations that should be made in choosing a suitable instrument for any particular purpose, from among the wide variety of thermometers available. The range of the thermometer is an obvious consideration; any thermometer has its own useful range. The thermal capacity of the thermometer may be of paramount importance for measuring rapidly changing temperatures, for a large thermometer whose thermal capacity will be large, will always lag behind the temperature changes of its surroundings, if these are rapid. For the accurate measurement of temperature, however, a large bath, thermostatically controlled, is essential, so that in this case a large thermal capacity is no objection. Obviously a thermometer of small capacity must be used for measuring the temperature of a small body. Ease and directness of reading are desirable features, especially for unskilled observers. Several factors concerning the accuracy of a thermometer should be considered. The sensitivity may be taken as the smallest detectable difference of temperature. Usually extreme sensitivity is associated with a limited range of temperature. A thermometer should be free from troublesome corrections and should give consistent results. Permanence of calibration is an extremely desirable feature unless convenient means of frequent calibration are available.

Mercury-in-Glass Thermometers

The precise nature of the temperature scale depends upon the glass used, but a temperature of 50° C. on the gas scale corresponds to about 50.1° C. or 50.2° C. on a mercury-in-glass scale. Owing to variation in the bore of the capillary, every mercury thermometer needs individual calibration on the international scale, unless very rough thermometry is suitable. Gas-filled mercury thermometers may be obtained reading up to 650° C.; if not gas-filled, care must be taken to see that mercury has not condensed in the upper part of the tube. If half-an-inch of the mercury thread is separated by applying a small luminous gas flame to the stem so that the mercury boils at that point, the thread will reunite upon cooling if the thermometer is gas-filled. The lower range of the thermometer is —39° C., which is the freezing point of mercury. The sensitivity of the thermometer depends upon the bulb size and the capillary bore; for a given temperature range the sensitivity can be increased only by increasing the length of the stem. The Beckmann thermometer (Fig. XV. 1) is a special modification with a sensitivity of about .001° C. and an extremely limited range of about 1° C., but the position of this 1° C. range can be varied at will over a much larger range. The thermometer has a very large working bulb and a very fine capillary, and is provided with a trap bulb at the top of the stem. By

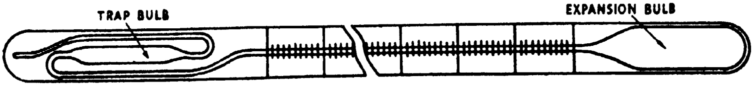


Fig. XV. 1. Beckmann thermometer.

heating it to just above the desired temperature range, the mercury fills the capillary and expands into the trap bulb. If the thermometer is now cooled the mercury recedes entirely into the working bulb, but the thermometer has been adjusted to read a small range of temperature slightly below the temperature to which it was heated. The value of a division on the stem depends upon the quantity of mercury in the working bulb, and, therefore, upon the range to which the thermometer has been set.

Simplicity and convenience are the chief advantages of the mercury thermometer ; precision work is accompanied by a number of troublesome corrections, for failure to immerse the stem completely in the measured temperature, for external pressure of the fluid on the bulb, for internal pressure of the mercury on the bulb, according to its angle to the vertical, and for the thermal hysteresis of the glass. Mercury thermometers often move in jerks, due to fouling of the mercury surface by traces of solids and gases on the walls of the capillary. In rough measurements the chief source of error of an unskilled observer is the parallax error due to observing the thermometer obliquely. This may be avoided by using a small telescope or by arranging the lighting and the thermometer so that an image of the scale is seen by reflexion in the mercury thread. The eye is placed so that this image is eclipsed by the scale itself in the vicinity of the end of the thread.

Thermocouples

If two dissimilar metal wires are joined at both ends to form a complete circuit, and if the two junctions are kept at different temperatures, an electric current will flow in the circuit, and can be measured by a galvanometer inserted therein (Fig. XV. 2). This phenomenon is used thermometrically by placing one junction in the temperature to be measured, and the other in melting ice. The electromotive force is measured most accurately by a potentiometer, or, more conveniently and with fair accuracy, by a moving coil millivoltmeter whose resistance is large compared with the resistance of the circuit. The magnitude of the e.m.f. depends upon the metals used but is of the order of 10 microvolts per °C. A thermocouple should be calibrated individually with the millivoltmeter with which it is to be used.

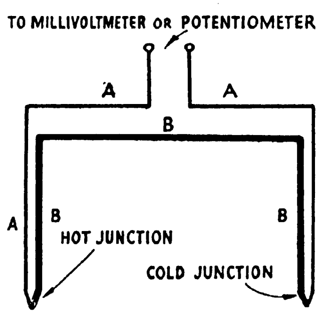


Fig. XV. 2. Wiring of thermocouple.

Any third metal may be introduced anywhere in the circuit without affecting its reading, provided the two ends of the third metal are at the same temperature. We may, therefore, use two copper wires to transfer the e.m.f. at the ice junction to the millivoltmeter or potentiometer ; furthermore, the hot junction may be soldered, welded or brazed, provided that the solder does not extent outside the uniform hot temperature. A practical form of thermometer is a rod of unglazed porcelain bored with two longitudinal holes in which the wires are threaded, and welded together where they project at one end. These wires must

continue from the other end of the rod to the ice junctions, insulated by glass beads if their temperature will be high in use. The ice junctions should be close together but insulated electrically, in a small glass tube immersed deeply in small lumps of ice from which the water is drained away. A wad of cotton wool or a small quantity of paraffin oil in the tube will keep the junctions uniformly at 0° C. Each junction is between one thermometer wire and a copper wire, and the two copper wires run from the junctions to the millivoltmeter or potentiometer.

Up to 300° C. a copper-constanton couple is fairly sensitive and has a nearly uniform graph of e.m.f. against temperature. Up to 1200° C. to 1500° C. platinum-platinum rhodium is a satisfactory couple. Near the maximum of the range, care must be taken to avoid corrosion of the wires. The thermocouple is an invaluable thermometer since it can be made with a very small thermal capacity, so that the speed of reading is limited only by the sluggishness of the moving coil meter. For consistent results it needs frequent calibration and scrupulous attention to details such as the purity of the metals, identical purity of the copper leads, and uniformity of temperature at the binding posts of the meter. Prolonged use at high temperatures is apt to cause changes of crystal structure in the wires and so to vitiate readings. Some couples are slightly sensitive to mechanical strain.

Platinum Resistance Thermometers

The electrical resistance of platinum, as that of most metals, increases with temperature, and this effect is used to measure the temperature of a winding of platinum wire in a porcelain or silica thermometer tube. The tube carries four terminals at its head ; two are used to connect the platinum wire to the Wheatstone bridge circuit for measuring its resistance, and the other two are connected together internally by a platinum wire running close beside the platinum leads to the thermometer wire (Fig. XV. 3). Externally these terminals are connected to the

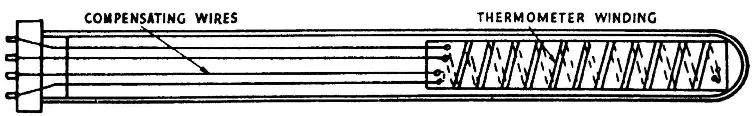


Fig. XV. 3. Platinum resistance thermometer.

arm of the bridge adjacent to the thermometer arm, by a pair of copper leads identical to the pair connecting the thermometer to the bridge, and the four leads are plaited together. The purpose of the second pair of leads is to compensate the thermometer circuit resistance for the resistance of the leads which vary in temperature to an uncontrolled extent. Any change in lead resistance results in equal resistance changes in the two adjacent arms of the bridge and so does not affect its balance. The bridge commonly used with this instrument is a special adaptation of the Wheatstone bridge known as the Callendar-Griffiths bridge (Fig. XV. 4). It is balanced by a step control of ten steps, and a fine adjustment on a slide-wire.

In its most elaborate form, this thermometer is the most accurate available. The great precision is obtained by following Callendar's specification for the method of measurement, and using the very exact calibration given by him, of the temperature scale of pure platinum against the gas scale.

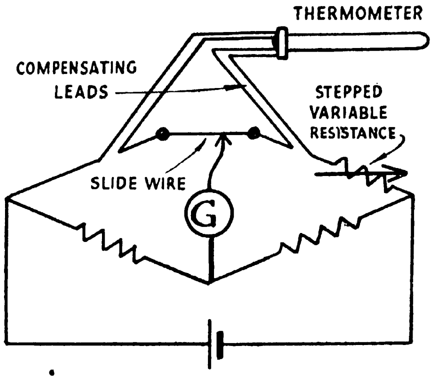


Fig. XV. 4. Wiring of platinum resistance thermometer bridge.

The maximum temperature is in the neighbourhood of 1000° C. to 1200° C. if mica is excluded from the construction of the thermometer ; above this temperature electrical insulation is difficult and the platinum is liable to contamination. It can also be used at extremely low temperatures, although for temperatures in the region of liquid air, etc., lead is more ensitive than platinum. It is evident that taking a temperature with this thermometer is not a speedy operation.

Pyrometers

The name pyrometer is usually given to an instrument which measures high temperatures (usually furnaces) by means of the radiation which they emit. They are of two main types, viz., full radiation, and optical, pyrometers. The first type measure the complete radiation, visible and invisible, emitted by the furnace. In one form, a concave mirror projects an image of the furnace presented to it, on to a small thermocouple, and the e.m.f. produced is a measure of the energy radiated by the furnace. Apertures in the "optical" system are arranged so that the reading shall be independent of the distance of the thermometer from the furnace. In a modification of this instrument, a helically wound bimetal strip such as is used in thermostats, replaces the thermocouple, and the rotation of the strip turns a needle over a dial marked directly in °C.

Optical pyrometers are more common ; they are simpler in construction and usually give more accurate results which are practically independent of their distance from the furnace. They depend upon projecting an image of the furnace on to the filament of a lamp, placed in the focal plane of a telescope, and an eyepiece allows the filament to be viewed against a background illuminated by the furnace. The filament current is varied until the filament just disappears in the background, neither brighter nor duller than the furnace. A reading of the filament current or voltage is then taken as a measure of the temperature. The range of the instrument can be extended to higher temperatures than that of the lamp, by inserting between the furnace and the instrument, red filters, or a revolving shutter which intercepts a known fraction of the light. These instruments need frequent calibration of the lamp for accurate results.

Vapour Pressure Thermometers

If a closed vessel is partly filled with a liquid, the liquid will evaporate until the vapour generates a pressure which depends upon the temperature, and is perfectly definite in value for any temperature. Since the increase of pressure for a given increase of temperature is quite large for volatile liquids, the phenomenon provides a sensitive thermometer. The range usefully measured depends upon the characteristics of the pressure meter; the pressure range corresponding to a given temperature range depends upon the liquid chosen, so that volatile liquids such as ether will measure lower ranges of temperature, water will suitably measure higher ranges, and liquefiable gases can be used for measuring extremely low temperatures. For the measurement of very low temperatures, a gas such as oxygen or hydrogen is used, and the pressure is measured by a mercury manometer. For high temperatures water or an oil are used with a Bourdon gauge. The thermometer has been used for industrial measurements, with an ether filling and a Bourdon gauge suitably modified for measuring low pressures.

Calibration of Thermometers

As has already been noted, the fixed points at which any centigrade thermometer must read 0° C. and 100° C. are the temperatures of melting ice and boiling water. For the lower fixed point, the thermometer is immersed deeply into a copper can filled with small lumps of ice prepared from distilled water. The lumps should preferably have been exposed for some time to room temperature, for the larger pieces from which they have been broken are often at a temperature below 0° C. The copper can should have drainage holes so that the water is removed as formed. It is an advantage to stand the can inside another and to fill the intervening space with ice. A mercury thermometer should be immersed to the whole height of the thread, and removed slightly to take the reading. Sometimes a mercury thermometer in an ice can will record a temperature below its true zero, and then revert to the true zero a few hours if kept in the can; this is due to a lag in the contraction of the glass on cooling. For this reason it is desirable and usual to calibrate the ice point before the steam point.

For calibrating the steam point, a simple apparatus called a hypsometer is used, which consists of a copper boiler with a double steam jacket around a copper tube above the boiler, through which the steam passes. The hypsometer is filled with distilled water so that the water level can be seen in the glass gauge fitted to it, and the thermometer is inserted through a bored bung in the copper tube, with the whole stem up to the steam point, immersed, and the bulb sufficiently above the water level to avoid splashing it when boiling. If the stem is not completely immersed, standard tables are available for the correction in this respect. The rate of boiling is varied to find a small range of rate of boiling over which the thermometer reading is steady; this rate is maintained until the reading is quite steady, and when taking the reading, the barometric pressure is noted. The precise boiling point of the water at this pressure can be found from standard tables.

For the calibration of the thermometer at other points on the International temperature scale, the use of a platinum resistance thermometer is specified up to 660° C., a platinum-platinum rhodium thermocouple for higher temperatures up to 1063° C., and an optical pyrometer for temperatures above this.

In making any accurate comparison of two thermometers they should be inserted close together in a bath of liquid suitable to the temperature range, of large dimensions, well-lagged and screened against loss of heat by radiation. Each comparison temperature should be thermostatically maintained for a long period, and the contents of the bath efficiently stirred during this time.

CHAPTER XVI

TIME

The measurement of time is one of the most fundamental and important in all human affairs. From the earliest days, the need for a means of measuring and recording time must have been apparent, but, as time is decidedly an abstract factor, accurate measurement cannot be directly achieved. The best method is to use a device which does work at an even speed, and to measure time in terms of the work done in a given period.

The first divisions of time were undoubtedly the hours of light and darkness, the apparent movement of the sun across the sky giving some rough idea of time of day. Later the change in the position of shadows of stationary objects suggested the sundial. At first this was probably a stick, set upright in the ground, with the convenient time divisions marked by stones. Later, the day was divided into regular time intervals, the beginnings of hours, minutes and seconds.

The need to measure time at night and on dull days led to other timekeepers, such as the water-clock or clepsydra, in which the even drip of water into or out of a vessel marked the intervals of time. Observation of the stars must have revealed that these had recurrent motions, somewhat like that of the sun, but to use these to give time indications must have been considerably more difficult. From the clepsydra evolved the sand-glass, employing sand instead of water. Lamps and candles also served as timekeepers, the amount of oil consumed being marked in one, and the burning of marked lengths giving a time reading with the other.

Early Mechanical Clocks

The introduction of mechanical clocks was the next step, though the period is uncertain, and the details of construction unknown. They were probably used by religious communities, who would have the greatest need for accuracy in the timing of their services. The earliest clocks were weight driven, had their timekeeping controlled by a fan or "fly," or a crude escapement of the roasting jack type, and denoted time intervals by striking a bell. Dials seem to have come later, a rather strange fact considering that the sundial long preceded the clock.

These early mechanical clocks were large machines, designed for erection in towers and turrets, and seem to have been quite elaborate. The most ancient remaining in England is dated 1386, and can still be seen in Salisbury Cathedral, but others dating from somewhat later times still exist in several places. Some have astronomical dials, which attempt to show the arrangement of the heavens, as it was then believed to be. Smaller clocks followed, the reduction in size bringing about much improvement of detail, and the invention of the mainspring as an alternative to the weight for providing motive power. Weights, however, are still the most constant source of power, and are used for many precision clocks.

The Pendulum

The next important development was the invention of the pendulum, the work of Galileo Galilei, about the year 1585. It was superior to any former device, for it enabled clocks to maintain reasonably accurate timekeeping for long periods, an advantage not possessed by the crude weighted-lever mechanisms that preceded it. The feature of the pendulum which makes it so valuable as a timekeeper is its isochronism, a term denoting that, within limits, its time of swing is a constant, despite variations in the arc through which it swings. It is, accordingly, able to measure intervals of time at an even rate, despite quite considerable variations in the power delivered by the clock mechanism.

The introduction of the pendulum soon caused the design of clocks to develop along lines similar to those adopted to-day, particularly in the case of regulators, and precision clocks used for astronomical work.

About the same time, another type of timekeeper began to assume a specialised form. At first known as portable clocks, these timekeepers soon received the more familiar title of watches. When the mainspring was invented, attempts were made to produce timekeepers which would function reliably when carried, but with disappointing results. When the application of the pendulum to clocks demonstrated the desirability of isochronism for good timekeeping, horologists sought for means to apply the principle to portable timepieces by using some other force to replace gravity.

Balance and Spring

This was achieved by using a wheel with a heavy rim, and controlling its motion by a light spring. The spring was mounted on the arbor of the wheel, and stored power when either coiled up or uncoiled beyond its normal position of rest. Coupled together, the wheel and spring formed a unit, the oscillations of which had a definite and isochronous periodic time, depending on the weight of the wheel and the strength of the spring. The assembly was called the balance and spring, and was at first used with an escapement very similar to that used for early clocks. Other escapements were later devised, including the lever, which is now standard on all good watches, and also on clocks where mobility is an essential feature.

Sea travel and navigation were developing rapidly at about the period that these improvements were being made, and it became necessary to find a reliable means of determining longitude at sea. Instruments for observing the stars and sun were greatly improved, but the real need was for a portable timekeeper which would give accurate time at sea, and so enable the navigator to determine his longitude. The problem became so urgent that an Act of Parliament was passed offering a reward of £20,000 "for an instrument which would enable longitude to be determined within half a degree." Many timekeepers attempted to meet the terms of the award, but it was finally won by John Harrison, whose fourth "chronometer" surpassed all requirements. From then until the present day, the "marine chronometer" has remained an extremely specialised type of timekeeper, unchallenged in its own sphere until the introduction of radio time signals, and still the standard timepiece for ships at sea.

The greatest development in horology since these inventions has been the application of electricity to clockwork. This revolutionary step involved the adoption of completely new principles, but effected remarkable improvements in standards of timekeeping.

Sidereal and Solar Time

Before dealing with the various forms of timekeepers at present in use, a few words on the two standards of time known as Sidereal and Mean Solar will not be out of place. The former, which is almost exclusively used for astronomical work, differs to some extent from Mean Solar time, which is that familiar to us all. Sidereal time is obtained from observation of the stars, and a sidereal day is the interval elapsing between two successive transits of an imaginary point, known as the First Point in Aries, across the observer's meridian. The instant of transit is sidereal noon, and the measurement of sidereal time is checked by observations of the transits of fixed stars. Mean solar time is obtained by taking an average of the transits of the sun across the meridian throughout the year and obtaining from it a measurement of time which is called a mean solar day. A mean solar day is longer by 3 minutes 55.91 seconds of mean solar time than a sidereal day.

Modern Mechanical Clocks

Present-day clocks are of two main classes, mechanical and electrical, and the principles of each type, though somewhat different, are fairly simple. In a mechanical clock, the source of power is alternatively a weight or spring, which stores sufficient energy to operate the clock mechanism for a certain length of time. When a weight is employed, it is usually hung on one end of a length of line, the opposite end of which is attached to the rim of a drum or barrel, pivoted on a spindle or arbor running in a bearing in the main clock frame. Winding up the line raises the weight, and the stored power can then be used to drive the clock. A toothed wheel coupled to the barrel by a ratchet serves to transmit this power to the rest of the wheelwork.

The spring used as an alternative form of motive power storage consists of a ribbon of high-grade steel, shaped into a loosely coiled form. If such a spring is wound into a closely-tightened coil, energy is stored in it by bending the steel ribbon along its entire length. The spring will give out most of this stored energy as it returns to normal form, and if suitably attached to the wheelwork of a clock, can be used to drive the mechanism.

In the commonest clocks, the spring is unenclosed, one end being fastened to the frame, and the other attached by a hooking catch to the arbor of the first or main wheel. Better quality clocks have their springs enclosed in a barrel, a cylindrical box which protects the spring and permits it to operate under better conditions. In most clocks the main-wheel is attached directly to this barrel, to which the outer end of the spring is also hooked, and the winding of the spring by turning of the central arbor causes the barrel and wheel to transmit power. This form of mounting is known as a going barrel. An alternative, sometimes used in precision clocks, is the provision of a fusee. The action of this device is to vary the power leverage of the mainspring

on the main wheel, and so to compensate for the somewhat variable power output which is the defect of even the best spring. The spring is mounted in its barrel, but is coupled to the main wheel, which is on a separate arbor, by a line or chain which winds round the conical fusee, and so alters the leverage as the power changes.

The wheelwork or train of a clock consists of a number of toothed wheels and pinions which transmit the power of the weight or spring to the escapement, where it is released in evenly-timed units by the action of the pendulum or balance. The ratios of the train wheels and pinions are chosen to enable this timing action of the escapement to be recorded on a dial in terms of hours, minutes, and sometimes seconds. The normal clock has four wheels, including the escape wheel of the escapement, and three pinions, though many eight-day clocks with going barrels have an extra or intermediate wheel and pinion between the main-wheel and the remainder of the train to provide a full eight-day run.

The Escapement

The escapement is the most important section of a mechanical clock. Its function is to release the energy stored in the driving weight or spring in an even and regular manner, and in correct proportional relation to the passing of time. This is done by allowing the escape wheel, which is mounted on the last arbor of the train, to move forward step by step, a distance of half a tooth space at a time. The teeth of the escape wheel are of special form, and engage in turn with the pallets (Fig. XVI. 1) which control their motion. These pallets, of which there are usually two, are so pivoted that as one advances, and engages with a tooth on the escape wheel, the other recedes a corresponding distance. As the spacing of the pallets in relation to the wheel is such that when a tooth is resting on either pallet, the other pallet is midway between two other teeth, this advancing and receding action will permit the wheel to escape a distance equal to half a space between two teeth at each movement of the pallets. This pallet movement is, in turn, controlled by the pendulum or balance, which thus ensures that the escape wheel is only able to advance at correctly timed intervals. The interaction of escape wheel and pallets has a dual purpose, for, in addition to

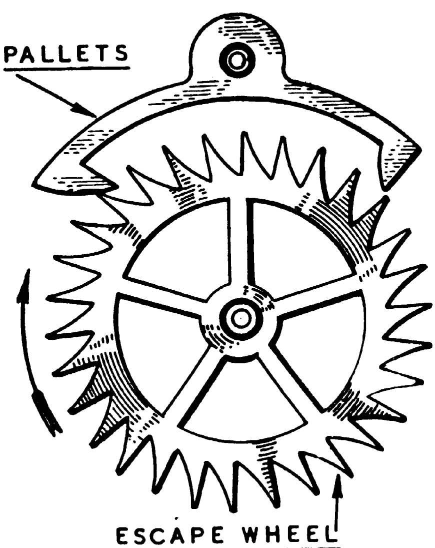


Fig. XVI. 1. Recoil escapement, as used on pendulum and domestic clocks.

being concerned with the timed release of the wheel train, both are so designed that a portion of the power transmitted by the escape wheel is transferred through the pallets to the pendulum or balance. This power is known as the impulse, and maintains the swing of the pendulum or balance by making good the losses due to friction. To give sufficient clearance for correct escapement action, the escape wheel is permitted a small amount of free movement between the point where one tooth drops off a pallet and the next tooth to act falls on the opposite pallet. This free movement is known as drop, and is the cause of the ticking sound made by a clock.

The pallets of pendulum clocks are usually linked to the pendulum by the crutch, which enables the motion of the pendulum to actuate the pallets and also transmits the impulses from the pallets to the pendulum. The pendulum is not pivoted, being hung from a firm support by a thin flat spring, known as a suspension. The periodic time of swing of a pendulum is adjusted by raising or lowering the mass, or bob, at the free end of the rod. This is done by a nut, running on a fine screw thread, usually located below the bob. Raising the bob shortens the periodic time, and lowering it has the contrary effect. The expansion and contraction of the pendulum rod as a result of variations of temperature can effect the periodic time in much the same way as an alteration of the bob, and to overcome this, pendulums are frequently fitted with a compensating device. This usually consists of an arrangement of tubes or rods of dissimilar metals, so arranged that their collective expansion or contraction neutralises changes in the length of the pendulum. An alloy, known as Invar has also been developed and this has such a small coefficient of expansion that its use for a rod renders the pendulum almost unaffected by changes of temperature.

Escapements using balances and balance-springs to control their timing differ somewhat in detail from pendulum escapements, though

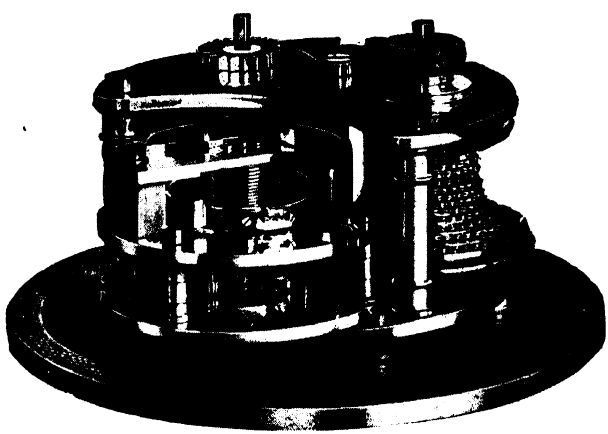


Fig. XVI. 2. Modern 8-day marine chronometer, one of the standard timekeepers for navigation. Chronometers of a similar type are also used extensively for surveying.

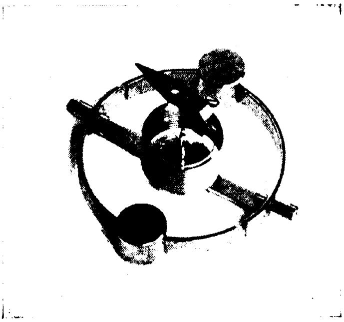


Fig. XVI. 3. A chronometer balance showing cylindrical balance-spring and bi-metallic rim with cuts.

their main principles are similar. The lever is the most widely used, its special virtue being that it is a detached escapement. The term detached means that the balance performs most of its swing when entirely disengaged from the rest of the escapement, and so operates under favourable conditions for maintaining good timekeeping. The less interference with the free swing of a balance or pendulum, the more constant is its measurement of time, and the design of an escapement aims to reduce such interference to a minimum.

In a chronometer escapement, the balance is even more detached than in a lever, for it only receives its impulse at alternate swings. The escape wheel impulses the balance directly, and as the balance makes its return swing it trips a very light spring.

Watches

The construction of watches is generally similar to that of mechanical clocks, the main differences being due to the reduced size. Most watch mainsprings are enclosed in going barrels, and the lever escapement is almost universal. Some high-class watches are fitted with the chronometer escapement, and are accordingly known as pocket chronometers. The limited power of a watch mainspring, and the need to reduce friction to a minimum has brought about the extensive use of jewels as bearings for the pivots of the train and escapement. Some precision clocks also employ jewelled bearings. The frictional efficiency of a steel pivot running in a jewel bearing is particularly high, and its durability is also excellent. The jewel stones are usually rubies, mostly of the synthetic variety, which have no intrinsic value, but assist greatly in ensuring the smooth transmission of power throughout the train.

Most watches run for about thirty hours with one winding of the main spring, and the ratios of the train provide for 18,000 swings or beats of the balance each hour. Some very small watches have faster trains, with the balances making 20,000, or even more beats per hour, and special timing watches used for recording small fractions of a second operate at even higher speeds, but in all cases the principles remain unaltered.

Mechanical timekeepers are often adapted to many special uses, and have attachments and constructional features which make them suitable for their individual duties, but to cover these would require a volume.

Turret Clocks

Another special form of timekeeper is the turret clock, the type used on churches and public buildings. The conditions in which these clocks operate, and the timekeeping required of them, entails special design and

construction. The frame is usually cast iron, and of the flat-bed form, this permitting any part to be adjusted or even removed and replaced without any interference with other parts. As weather conditions can affect the hands of these clocks, a special escapement, known as the gravity, and invented by the late Lord Grimthorpe for the Houses of Parliament clock at Westminster, is used instead of the kinds used on smaller clocks. This escapement maintains the swing of the pendulum

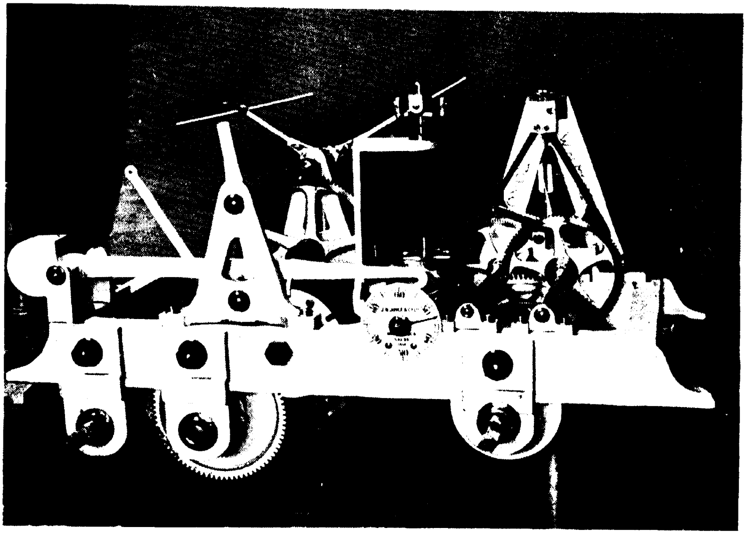


Fig. XVI. 4. A modern turret clock movement, using the gravity escapement, and striking the hours. The timekeeping mechanism is on the right, and the striking mechanism on the left.

by the impulses given by two weighted arms which are raised and locked by the escape wheel, and are unlocked by the pendulum as it makes contact with each in turn. The unlocked arm then descends with the pendulum a distance equal to that which it was raised by the escape wheel, and in so doing delivers its impulse. By this means the escape wheel only delivers an impulse indirectly, and, as the weight of the descending arm is always constant, the impulse is as nearly as possible invariable. Many other refinements are also fitted to turret clocks to improve their performance, and if properly constructed and maintained, these timekeepers can maintain extremely accurate time over quite long periods.

Electric Clocks

The electrical operation of clocks has led to alterations of design, and, generally speaking, to a great simplification. There is a distinction between true electrical clocks and the electrically wound types, which are merely mechanical clocks fitted with automatic electric winding

attachments. The truly electrical clocks are those in which electrical power supplies the energy to maintain the swing of the pendulum, either directly or by means of some gravitational device which is reset electrically. The latter method is used by most systems, and has proved very successful, largely because of the accuracy of timekeeping and great reliability obtained. The excellence of timekeeping is due to the almost unimpaired freedom of swing afforded to the pendulum, the simple mechanism, which has only one wheel, and the even gravitational impulse to the pendulum. The Synchronome claims to be the oldest of the various systems using this principle, and the master clock made by this firm will serve quite well as a type for purposes of description.

The pendulum, having an Invar rod and a heavy cylindrical bob, is hung from a bracket at the top of the main casting which carries the rest of the mechanism. Near the top of the rod, on a level with the rest of the mechanism, is mounted a pallet, having a curved acting surface by which the impulse is given to the pendulum. Just below this pallet is fixed a thin springy arm, which carries a semi-circular gathering jewel at its remote end, and on the base, at a point where its teeth can be gathered by this jewel, is a 15-toothed ratchet wheel, pivoted on an arbor. As the pendulum swings, it causes the gathering jewel to alternately trip over and gather the teeth of the ratchet wheel, a swing in one direction causing the jewel to step over the tip of a tooth, and the return swing to draw this tooth round until the jewel has moved far enough to disengage from it. One tooth is gathered at each return swing of the pendulum, and as the wheel has 15 teeth, and the pendulum makes one swing per second, the wheel will make one complete rotation every 30 seconds.

A small vane is also mounted on the arbor of the 15-toothed wheel, and at each complete rotation of the wheel this vane engages with and trips a spring-loaded catch which normally supports one end of a right-angled gravity arm, pivoted at its point of angle, and located on the base plate in such a manner that it can fall a short distance when the spring catch is drawn aside. As the catch is tripped and the gravity arm descends, a small roller pivoted on a bracket on the arm, drops on to the pallet previously mentioned as being on the pendulum rod, and then rolls down the curved pallet face. This action causes the weight of the arm to deliver an impulse to the pendulum sufficient to maintain its swing until the end of the next half-minute, when the process is repeated. When the roller reaches the end of its path down the pallet, the other angle of the gravity arm moves to a point where a contact mounted on it meets another similar contact fitted to the end of a pivoted armature. As this occurs, the circuit through the two contacts is completed, and the magnet which attracts the armature is energised. This causes the armature to replace the gravity arm on its spring catch, where it awaits the repetition of the cycle at the conclusion of the next thirty seconds. Completion of the circuit energising the electro-magnet and replacing the gravity arm also records time by operating special impulse-driven dials for the series of electric impulses which occur at exactly half-minute intervals are utilised to energise the dial mechanism.

The dials and the master clock are connected in series, and mounted on the minute hand spindle of each dial is a 120-toothed ratchet wheel.

Engaging with these ratchet teeth is a pawl, coupled to an electro-magnetically actuated armature which is attracted to its magnet at each impulse. This causes the pawl to step back and drop into the next tooth of the ratchet wheel, tensioning a small spring as it does so. The conclusion of the impulse allows the armature to return under the power of the spring, and so propel the hands forward a distance indicating one half-minute. If the battery power is suitably increased, a large number of dials can be included in the master clock circuit, all in series, and all making the necessary step forward when the impulse is transmitted by the master clock.

The master clocks and impulse dials of other similar systems differ in detail from those described, but variations are small. There are other types, however, which dispense with the gravity arm principle and use direct magnetic impulses to maintain the arc of the pendulum. In this type of clock, the impulsing magnet usually acts upon an armature attached to the pendulum, current being automatically applied to the windings of the magnet as soon as the arc of the pendulum falls below a certain point. As the timing of this impulse may be variable, it is usually necessary to provide additional contacts to close the circuit operating the impulse dials at regular intervals instead of using the maintenance impulse of the master clock for both purposes.

The most notable development of the electric master clock from a timekeeping standpoint is the Synchronome-Shortt "Free Pendulum," which is an amplification of the more ordinary type of master clock already described. It is an established principle of precision timekeeping that the less interference to which a pendulum is subjected, the more accurate is its time of swing. Even the friction of the air constitutes interference, the degree of which will vary with changes of atmospheric density.

In the ordinary master clock, used for driving circuits of impulse dials, interference from mechanical causes is very small, but the pendulum still has to engage its gathering jewel with the teeth of the ratchet-wheel, draw the wheel round, step-by-step, and trip the gravity arm catch every thirty seconds. These actions are all interference with the free swing of the pendulum, and even the travel of the roller on the gravity arm down its track on the pendulum impulse pallet is an interference, though an unavoidable one. As most of the interference with the pendulum of the master clock comes from the gathering jewel and the work it does in releasing the gravity arm, it follows that if the gravity arm could be released at the correct instant by some external control, the pendulum would be freed from all disturbing influences except those due to the delivery of the maintenance impulse. In the Shortt free-pendulum clock, this is achieved by linking two clocks, one being the free pendulum and the other the "slave" clock, kept in step with the free pendulum by a synchronising device, and serving to release the gravity arm of the free pendulum by the fall of its own arm every 30 seconds. The free pendulum swings in a sealed case, exhausted to a partial vacuum. Its gravity arm is of very light weight, and rests upon a spring-loaded catch which is tripped by an electro-magnet energised by the slave clock. The construction of this slave clock is identical with that of an ordinary master clock, but it has an additional syn-

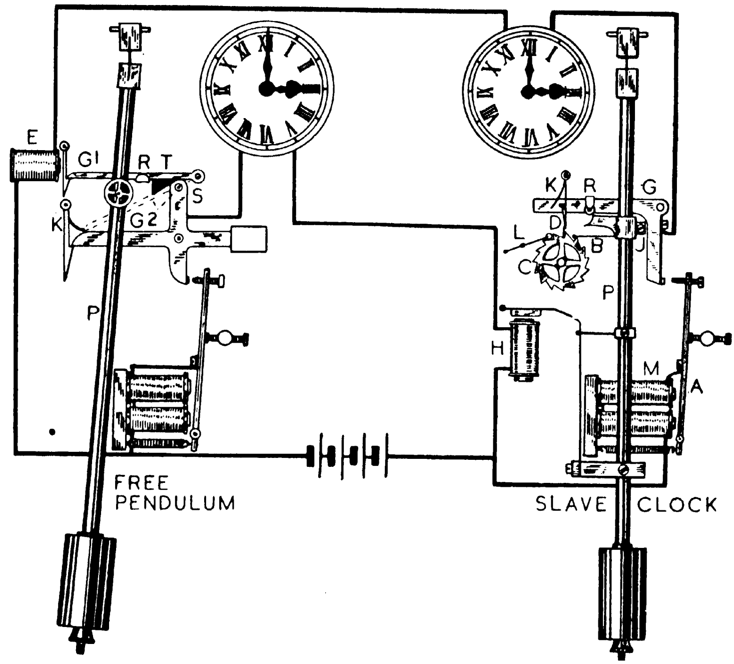


Fig. XVI. 5. Schematic diagram of the Synchronome-Shortt free pendulum. In the slave clock the letters are as follows: P, Pendulum; A, Armature; M, Magnet; C, Ratchet wheel; J, Impulse pallet; G, Gravity arm; R, Roller; K, Catch; B, Gathering jewel; D, Vane; L, Backstop lock; H, Synchronising magnet and armature.
On the free pendulum the letters are as follows: P, Pendulum; G1, Impulsing gravity arm; E, Gravity arm release magnet; G2, Re-setting gravity arm; K, Re-setting arm catch; R, roller pallet; T, Re-setting cam.

chroniser by which it is governed by the free pendulum. When the clocks are in operation, their synchronisation ensures that the slave clock will release its own gravity arm just as the free pendulum *approaches* the correct point in its swing for the reception of its impulse. The completion of the circuit by the descent of the slave clock gravity arm energises the slave replacement circuit, and effects the raising of the arm in the usual way, but it also energises the magnetic trip which releases the gravity arm of the free pendulum. This arm delivers its impulse as it descends on a roller on the pendulum rod, and then, as it drops right off the roller, trips a light catch holding up a heavier, subsidiary, gravity arm. This arm falls in turn, raising the impulsing arm and making a contact which energises both its own replacement magnet and the magnet of the synchroniser on the slave clock. This synchroniser is so arranged that if the slave pendulum is slow, it is automatically accelerated, but if it is correctly timed, it is left unaltered in timing.

This form of construction so greatly improves the conditions in which the pendulum operates that the performance of the free pendulum clock is superior to that of any other pendulum timekeeper, and has won for it a premier position in observatories all over the world. The first challenge to it comes from the quartz crystal clock, which will be described in its place.

The Synchronous Electric Clock

Mention should be made of the synchronous electric clock, operated from the A.C. supply mains, which is probably the most popular of all electrical timekeepers. Although this form of clock has undoubtedly brought reasonably accurate timekeeping to a much wider public than any other, it is not really a clock at all, being merely a form of impulse-driven dial, receiving its impulse many times per second instead of twice per minute, and being completely dependant on external control for its timekeeping. Actually it is a frequency meter, consisting of a small synchronous motor, driving a suitable reduction gearing at a speed which keeps the hands of the clock indicating correct time whilst the supply current is maintained at the correct frequency, which, in Britain, is 50 cycles per second. If the frequency increases, the clocks will gain, but if, conversely it decreases the clocks will lose. From this it is apparent that the A.C. mains merely form a time distribution system, kept accurate by reference to a standard master clock. The type of clock used to control A.C. frequency is usually an electric master of the type previously described, but fitted with a seconds counter of the impulse type. A dial driven by such a clock is compared with one driven by a synchronous motor, and when the time shown by the synchronous dial shows a divergence, the power station staff adjust the speed of the alternators to make the necessary correction. Later it may be possible to devise automatic control, but this is not used at present.

The Quartz Crystal Clock

The quartz crystal clock, the most recent development in timekeeping, is entirely novel in principle. Its action depends on the fact that if an electric voltage is applied to the faces of a piece of quartz crystal, the crystal will undergo a slight change of shape in a direction at right angles to the points of application of the voltage. When the voltage is removed, the crystal will return to its former shape. If an alternating current of a frequency approximately equal to the natural frequency of the crystal is applied in this way, the changes of shape will occur at the natural frequency of the crystal, and become vibrations or oscillations. The important feature of these oscillations is that they can control and keep constant the frequency of the applied alternating current at a value in synchronism with the natural frequency of the crystal. In practice, the applied alternating current is provided by a thermionic valve circuit, and the resultant controlled frequency current, whose value is kept constant by the resonance of the crystal, is amplified by a series of thermionic valves to a point where it can be used to drive a synchronous motor. The frequency of the crystal controlled current is far too high for direct use, being some 10,000 cycles per second, and to reduce this a sub-multiple generator circuit is employed. This is, in effect, an elec-

trical reduction gear, controlled by current at crystal frequency, but delivering current at a much lower frequency which is an exact sub-multiple of it. This lower frequency current, which has a value of about 1,000 cycles per second, is used to operate the synchronous motor, the latter being coupled to the dial of the clock by a reduction gear of the normal type. The synchronous motor somewhat resembles that used for the familiar mains-operated A.C. clock, but is designed to operate at 1,000 cycles instead of the normal 50 cycles.

The frequency reduction effected by the sub-multiple generator circuit, and the reduction gearing of the clock train are so selected that when the crystal has its natural frequency of vibration exactly, the clock will show accurate time. From this it will be apparent that the timekeeping of the clock depends entirely on the constancy of vibration of the crystal. This in turn, is dependent on the conditions under which the crystal operates, such as temperature, pressure and so on. Most of these influences can be kept under control. At the present time, the clock is still in a state of development, but it has already demonstrated its capabilities as a very high precision timekeeper.

In this brief survey of the instruments used for timekeeping, we have traced their development from the crude stick sundial to the quartz crystal clock. In few, if any, of the developments of scientific research has man achieved such a near approach to perfection. In the crystal clock deviations from the mean as small as one part in a hundred million have been discerned, and the most accurate of our time measuring instruments have even shown variations in such things as the motion of the earth itself. Even so, the ultimate goal has not been reached, for further advances are even now on the way.

CHAPTER XVII

SPEED

The speed of travel of an object is the rate of change of position with time, thus it can be determined by finding the time required for the traversal of a measured distance. This fundamental method generally gives the greatest accuracy, but ordinarily the quotient is determined instrumentally, and shown by a pointer moving over a scale, or by a pen tracing the value continuously on a chart. The principles employed in these instruments depend on the medium in which the object is moving, and will be discussed under three main headings, (1) the land speed of objects moving on the land, (2) the air speed of objects moving in the air, and (3) the water speed of vessels travelling on the water. No attempt will be made to deal with the problems of navigation which arise in the determination of the land speed of air or water-borne craft.

Land Speed

When low speeds have to be measured the fundamental method can be applied with the simplest of equipment; a yard-stick to measure distance, and a stop-watch to measure time. These, and possibly two observers, are all that is required to give results of normal accuracy, and for years they have sufficed to record the speed of travel of man and beast, but as speeds increased greater precision became necessary and the chronograph was evolved from the ⅕ sec. stop-watch. But as speeds rose further, and competition became keener, the human element had to be eliminated, and electrical methods were introduced. These usually involve placing at a known distance apart two devices which give electrical impulses as the travelling object passes them. A wheeled vehicle can conveniently operate contact strips laid on the ground, whilst photo-electric apparatus, which involves the interruption of a light beam, has wide fields of application. The breaking of a tape, too, can be made to open or close contacts.

The electrical impulses may be used in a number of ways. The most accurate method, particularly for short time intervals, is to record photographically the deflections of an oscillograph or of a string galvanometer concurrently with a standard time signal. Alternatively, they may be made to deflect pens making traces on a strip of paper drawn continuously under them by a motor, and on which another pen is recording standard time signals. This method is particularly suitable for measuring longer time intervals when otherwise the consumption of photographic material might be excessive. Direct readings may be obtained from the impulses if they are made to trip time measuring devices. Thus they can control magnetic clutches on a continuously running clock mechanism, or if magnified by relay can be made to work an electro-magnetic clapper device applied directly to the knob of a stop-watch; simply replacing manual operation.

Speedometers

The foregoing fundamental methods are used to measure vehicular speeds only when academic accuracy is required, and normally instruments called speedometers are carried for this purpose, and operated either mechanically or electrically from the road-wheels. Early types were driven from the front wheels of motor vehicles through a friction driven shaft to which was coupled a flexible shaft of sufficient length to reach the speedometer itself, but in more recent years it has become general practice to take the drive from the transmission, and provision is often made for it in the gearbox. These instruments usually display a counter, or odometer showing the mileage travelled in addition to the speed pointer. There is a limit to the length of flexible shaft which will give satisfactory service so electrical instruments are useful on large vehicles. These comprise a small generator connected to the indicating head by 2 or 3-core cable, and since this can be of quite appreciable length, the two components can be put in the most convenient positions.

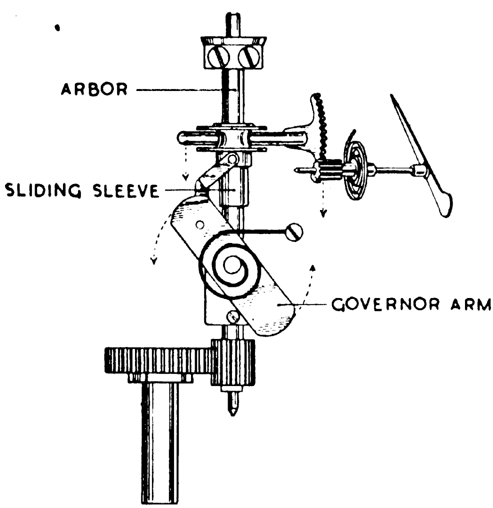


Fig. XVII. 1. Principles of the centrifugal speedometer.

Mechanical Speedometers. Instruments driven through a flexible shaft, i.e. mechanically driven, employ one of three general principles. The earliest instruments used centrifugal force as their basis, and some of this type are still made, being commonly referred to as "governor" instruments because of the similarity of their mechanism to that seen on some steam engines. The design usually comprises a pair of weights carried round by a governor arm and hinged to a rotating arbor as shown in Fig. XVII. 1. The weights are thrown outwards by centrifugal force, against the constraint of a spring, thus the distance the governor arm is displaced is a measure of the rate of rotation, which is obviously proportional to the road speed of the vehicle. It will be seen that the arm is linked to a sliding sleeve on the arbor, and it is through this that the position of the weights control the instrument pointer. Instruments of this type have the advantage that their readings are independent of the direction of drive, but they have the disadvantage that they require to be driven at a rather high speed which increases the strain on the flexible shaft.

These "governor" instruments have now been very largely replaced by those using the eddy-current principle, and illustrated by the classical experiment known as Arago's Disc. These are usually referred to as "magnetic" instruments, for the driven shaft carries a permanent magnet, which as it turns produces a rotating magnetic field in a cylindrical or annular air-gap. A "drag-cup" or disc of aluminium or other good conductor is mounted on a pivoted spindle so as to swing in this gap with the magnetic field passing through it. Thus, as the magnet revolves, eddy-currents are generated in the drag element which is pulled round against a restraining spring. The forces produced are directly proportional to the speed of the magnet, so the instrument has a uniform scale. These mechanisms can be designed for the most economical production, but may also be refined to give great accuracy. The major difficulty is to compensate for the change with temperature of the electrical conductivity of the drag element, for this has a proportional effect on the readings. Normal requirements are met by applying a shunt of thermo-magnetic alloy to the magnet. These instruments usually develop enough torque in the drag element to give reliable readings at comparatively low speeds of rotation; indeed this condition is essential if the pointer movements are to be sufficiently damped, thus the demands on the flexible drive are not so severe as for "governor" instruments, and a longer length can be tolerated. The pointer turns in the same direction as the magnet, consequently instruments have to be calibrated for a particular direction of rotation, unless some mechanical device is added to cause the magnet to turn always in the same direction, whichever way the driving shaft revolves.

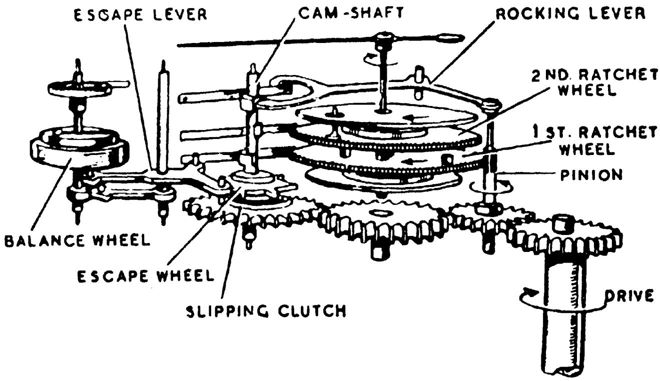


Fig. XVII. 2. Chronometric principle.

The third class of speedometers employ the "chronometric" principle and work out mechanically the quotient of time into distance. The mechanism of a typical instrument will be described with reference to Fig. XVII. 2. The centre of interest is the camshaft, for this provides the time-base, and in addition to the cam carries an escape wheel which together with an escape lever, and balance-wheel, constitutes a complete

escapement. Thus as the camshaft is driven through the slipping clutch it is constrained to run at a constant speed in exactly the same way as is a timepiece, and the three cams will move the spring fingers in contact with them in a regular sequence at constant time intervals. The top cam controls the rocking lever, which, at the beginning of the sequence moves the pinion into mesh with the first ratchet wheel. The pinion is driven continuously by the road-wheels, so the distance it turns the ratchet wheel during the constant time of contact with it is dependent on the speed of the vehicle. This first ratchet wheel carries a peg which can engage with a similar one on the second ratchet wheel, so that as the first is moved round it can pick up the second ratchet wheel and carry it round too, and the pointer with it. The continued rotation of the camshaft causes the pinion to move out of mesh with the first ratchet wheel, and then momentarily releases the ratchet on the second ratchet wheel, so that if in the previous cycle the pin on this second ratchet wheel had been left above the point to which the first wheel had been carried it will now drop back to it under the influence of the control spring, taking the pointer as well. Thus in actuality, the pointer shows the position of the pin on the first ratchet wheel.

The bottom cam then releases the ratchet on the first wheel, when this is returned to its starting point by its spring, and is ready to commence the cycle all over again. The pointer naturally moves in jerks from one reading to the next but as the cycle is repeated about every second the maximum change that can take place between each is limited to an amount which is not serious. The chief limitation of the instrument is that it will not record speeds below that at which the clutch begins to slip and the driving spindle must always turn in the right direction. This is usually ensured by the insertion of an automatic jockey gear.

Electrical Speedometers. The indicating portion of an electrical speedometer is a voltmeter adapted to measure the output of the generator. This usually has a permanent magnetic field, and can be designed to generate either direct or alternating current, the output voltage varying substantially with speed. A direct current system permits the use of a high-grade moving-coil voltmeter or of a moving-iron instrument, according to the accuracy desired, but the commutator with its brushes may need periodic attention for consistent results. This weakness is eliminated with an alternating system, but there is some difficulty in finding voltmeters for alternating current which give the same accuracy as the D.C. counterparts without imposing a greater load on the generator. This is important, for if the readings are to be independent of the generator temperature, which may vary considerably in service, the resistance of the indicating instrument must be many times that of the generator. Voltmeters for A.C. are based on one of four principles: moving-iron, induction, dynamometer, and D.C. moving-coil with rectifier, and in making a choice from among these it must be remembered that the output from the generator will vary in frequency as well as in voltage. Consequently, the first two types will have non-uniform speed scales, the lower portion being extremely cramped, but the induction type can give an almost full circle scale, and is suitable for normal technical use. The dynamometer unfortunately has a square law scale, and tends to

impose a heavy load, consequently the rectifier instrument is the most attractive, and is now quite satisfactory. The accuracy of this equipment does depend on the generator retaining its calibration but this is not difficult to ensure with modern magnetic alloys.

Air Speed

The precise determination of aircraft speed is a problem of great technical difficulty, and is the subject of continuous research. The time required to pass two fixed points of the ground speed can be measured accurately with modern apparatus as long as the craft is near to the ground, but the deduction of the airpseed from this data demands that the direction and velocity of the wind shall also be known with equal precision. Consequently most measurements of air speed are made with apparatus carried by the aircraft itself, comprising a pitot-static tube fixed to the airframe, and connected to a differential pressure gauge. Fig. XVII. 3 shows the principle.

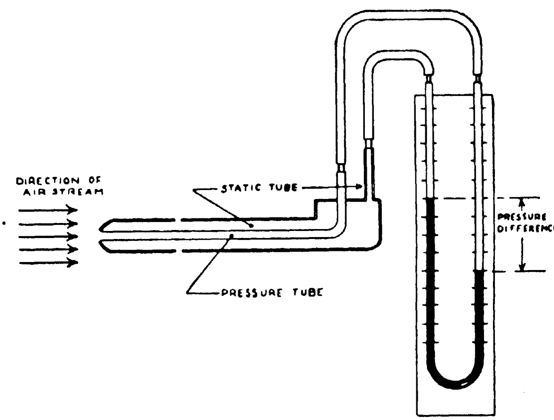


Fig. XVII. 3. Principle of pitot-static head.

The pitot-static tube assembly consists of two concentric tubes. The inner one has an aperture pointing into the airstream, and receiving the impact or "ram" pressure, whilst the other, with the holes in the cylindrical surface, measures the static pressure of the atmosphere. The difference between these two pressures is, at low air speeds, equal to half the product of the air density, and the square of the speed, but at high speeds other terms, dependent on the compressibility of the air, become of importance, and cannot be neglected.

The indicator itself (Fig. XVII. 4) commonly has a flexible capsule and magnifying mechanism mounted in an airtight case. This case is connected to the static tube, whilst the capsule receives the impact pressure. Thus its distension is dependent on the difference between the two, and this is shown by the pointer moving over a scale calibrated in miles per hour, knots, or other units. According to the relationship quoted above, the pressure is proportional to the square of the speed,

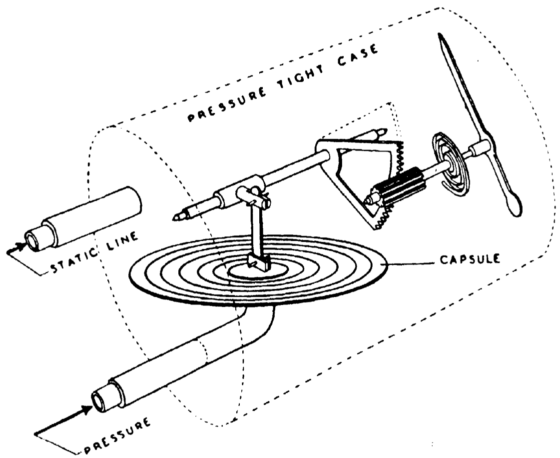


Fig. XVII. 4. Airspeed indicator.

and this tends to make the scale become more open at the higher readings. Whilst this might be useful for navigational purposes it is very undesirable from the pilot's point of view, because he is acutely interested in the lower values in the neighbourhood of the stall, which he must read with great facility. Therefore the mechanism must be designed to compensate for this effect in conjunction with suitable capsule characteristics. In this way it is possible to produce an instrument with a perfectly uniform scale over a pressure range of 100 : 1, that is a speed range of 10 : 1.

It is to be noted that the readings of this instrument are proportional to the density of the air, and since this falls progressively with increasing altitude an airspeed indicator as outlined above will be correct at one atmospheric pressure only, and in fact calibration is usually made for standard sea-level conditions. The readings of such an instrument are referred to as "indicated airspeed" and satisfy the pilots' requirements as far as the handling of normal aircraft is concerned, for the same factors which affect the readings of the indicator control the aerodynamic forces on the aeroplane. But the navigator must know the "true" airspeed, and this requires the application of a density correction. Several attempts have been made to apply this correction in the instrument itself, but logically this involves not only the measurement of the atmospheric pressure, which can be obtained from the static line, but also the measurement of the air temperature at the pitot head, and when an instrument has been designed to correlate these mechanically, the result has usually been extremely complicated. These instruments do not find general favour, however, for navigation is an exact science, and preferred results are obtained by calculation using corrections based on the measurement of air temperature and pressure by separate instruments whose individual performances are known.

Modern instruments can be made so precisely that in practice the overall accuracy of an installation is much more likely to be limited by

errors arising in the pitot head than from those in the instrument. Theoretically the pitot head should be mounted with its axis parallel with the air-stream, and in that part of it which is unaffected by the passage of the aircraft itself. Consequently it is usually fixed on a support or strut in front of, or well below the leading edge of the wing, or under the fuselage. Unfortunately, aircraft change their attitude of flight according to loading and speed, and the region of disturbed air changes too, so that in practice the best position on any new aircraft has to be found by experiment. As the aeroplane changes its attitude the axis of the pitot tube will cease to be parallel with the direction of flight, but it is not difficult to proportion the head so that this factor does not cause serious errors.

The pitot head can be rendered completely useless by a deposit of ice, and this may imperil the aircraft and crew, so it is usual to build an electric heater into it to be switched on when conditions require it. Precautions have to be taken in an installation to ensure that water which cannot be entirely excluded from the system does not collect in a bend and cause a stoppage.

Airspeed indicators have been made in other ways. On some types of elementary aircraft the indicator consisted of no more than a sprung vane mounted on a strut where it is visible, and deflected by the air-stream over a graduated scale. Another variety comprises an airscrew mounted forward of the wing. It is driven round by the air-stream and electrical means are used to show its speed of revolution. Actually this instrument always shows the true airspeed so it can be used for navigational purposes, and can provide a record of air miles flown, but it was never used to any extent because of its vulnerability, and the difficulty of giving protection against ice.

Water Speed

This is usually measured in terms of nautical miles (of 6,080 feet) per hour, expressed as "knots." This word originates in the means by which these speeds used to be found, that is, by means of a "log." This was a piece of wood attached to a long length of cord having knots tied in it at certain equal distances and coiled up on a reel. When the log was thrown overboard the cord was pulled out and the number of knots which passed in a certain time were a measure of the ship's speed. The certain time must bear the same relation to the hour as the distances between the knots do to the nautical mile.

This way has obvious disadvantages and so instrumental methods have come along, giving not only a continuous indication of speed but also a record of sea miles travelled. Some of these improved "logs" use the same principles as the air-speed indicators, one or two types using the pitot-static tube. This is designed to project some distance from the bottom of the ship so as to be clear of the water which is dragged along by the skin of the ship. It is provided with "pressure" and "static" orifices and the difference of pressure produced by the motion of the ship are transmitted by pipes to an instrument within the hull, but situated below the water-line to permit the elimination of air. This converts the pressure difference into a proportional electric current operating remote indicators on the bridge or in the chart room. The conversion

may be achieved by mechanical means or through a mercurial manometer. It should be noted in passing that the relation between speed and pressure follows a square law as in the air-speed indicator, so that accuracy will be greater at higher speeds.

Fig. XVII. 5. A 'patent log' giving the distance run through the water by a (small) ship, showing the rotor trailed through the water and connected by a plaited line to the recording head mounted on the ship—usually on the taffrail.

Another type uses a screw or propellor, which when mounted in the stream will spin at a rate dependent on the pitch of the blades, and steaming speed, provided that it has to do no work. The most simple form has a cylindrical body tapering to a point in front where it has a ring for attachment to a line. The cylindrical part has three fins arranged in a helix forcing it to turn as it is drawn through the water, and a given number of revolutions correspond to a definite distance of travel, so the forward end of the line is attached to an instrument, which by means of gearing shows the distance travelled on a dial. The instrument head is conveniently mounted on a strut off the ship's quarter so that the screw member is free of water disturbed by the ship itself. Mechanical or electrical transmission may be used to give readings at other locations. Another form carries the screw on an arm that can be projected from the ship's bottom, and in this case it is required to work only a pair of electrical contacts. Each closure of these corresponds to a certain distance travelled, so the total can be recorded by a simple electro-magnet and ratchet mechanism. If it is desired to show speed, then a time base must be introduced by a clockwork device, and such arrangements are not unlike the "chronometric" speedometer described earlier. As in the case of other electrical instruments, readings can be made available at various points on the ship.

It is possible to calculate the speed from the revolutions of the ship's propellor, and to-day the corrections which have to be applied can be determined with such accuracy that mariners often prefer this method of obtaining their speed. Electrical tachometers, such as those described earlier in this article are suitable for this purpose because they can provide the reading on the bridge, or at any other station remote from the engines.

CHAPTER XVIII

WEIGHT

Weighing machines operate on the principle of obtaining a state of equilibrium between two forces, one of the forces being the weight of the mass being weighed, and the other either the weight of a standard mass or the force exerted by a body in resisting elastic deformation, as in a spring balance or torsion balance. A simple or compound lever system is embodied in most weighing machines, the simplest form of which, an equal armed lever, being used in the balance.

The Balance

A balance consists of a beam pivoted at its centre on a knife edge called the fulcrum, and the pans, one for the load and the other for the standard weights, are suspended from each end of the beam. For a balance to be true, i.e. for the beam to assume a horizontal position, when the balance is both unloaded and loaded with equal masses, the following conditions must be satisfied :—

(a) The moments of the weights of the arms of the beam, about the fulcrum, must be equal.
(b) The two scale pans must be of equal weight.
(c) The distances between the points of suspension of the pans and the fulcrum, must be equal. In order to ensure this equality the pans are suspended on knife edges which are fixed to the beam.

Errors in (b) and (c) might counteract each other, but will not do so if the pans are interchanged.

A balance must also be stable, i.e. the beam, if disturbed, will oscillate or vibrate, and ultimately come to rest in its initial position. For this to be so the centre of gravity of the beam must lie below the fulcrum.

For a balance to be capable of accurate weighing, it must be sensitive to small differences between the loads suspended from the terminal knife edges, by giving an appreciable deviation of the beam from the horizontal. If the loads in the two pans differ by an amount w and the beam deviates an angle α from the horizontal, the sensitivity is measured by the ratio $\frac{\tan \alpha}{w}$. For a beam in which the three knife edges are in line $\frac{\tan \alpha}{w} = \frac{L}{W \times d}$, where L is the length of each arm, W the weight of the beam, and d the distance between the fulcrum and the centre of gravity of the beam. If the fulcrum is above the line joining the terminal knife edges the beam is less sensitive, and its sensitivity decreases with increase of load. In practice the fulcrum is positioned slightly below the line joining the terminal knife edges, so that the bending of the beam when loaded tends to bring the knife edges into line. Care must be taken that the fulcrum is not placed too low, or the centre of gravity of the beam might coincide with, or lie above, the fulcrum, establishing neutral or unstable equilibrium of the beam.

A balance is provided with a mechanism for raising the beam from the fulcrum support and for lifting the pans from the terminal knife edges whilst the load and weights are being applied. When the beam and pans are lowered onto their supports, the beam is free to vibrate, ultimately coming to rest at the rest point. A pointer attached to the beam indicates on a scale any deviation of the beam from the horizontal. In a balance which is not highly accurate the weights are adjusted until the beam comes to rest in a horizontal position. In a very sensitive balance the registered deviation is corrected to the amount of weight required for perfect balance, by reference to a sensitivity chart for the balance. The pointer is sometimes used to carry a small weight which can be raised or lowered so that the centre of gravity of the beam can be adjusted.

A finer degree of accuracy than is possible with the smallest weight can be obtained by the use of a rider. A rider is a small weight made of wire so that it can be placed over a graduated horizontal scale attached to the beam. If the rider weight is 0.005 gr. and the scale is graduated into ten divisions, the beam balancing with the rider at zero, when the rider is on division x the corresponding addition to the scale pan weight is $\frac{x}{10} \times 0.005$ gr. By the use of riders and a sensitivity chart a very high degree of accuracy is obtainable; for instance, a precision balance with a capacity of 10 gr. is capable of making a weighing to 0.000001 gr.

The finer the sensitivity of the balance the longer time will the beam vibrate before coming to rest. The rest point can be estimated by averaging the divisions registered by the pointer at the extremities of the swing. A damping device is sometimes used, in the form of a flat plate which is fixed to the end of the beam and which oscillates in a closed cylinder containing air, as the beam swings.

Gram-Chain Balance.

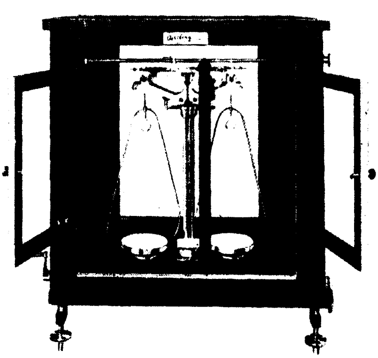


Fig. XVIII. 1. Gram-chain balance.

The gram-chain balance (Fig. XVIII. 1) is a type which renders possible a high degree of accuracy combined with speed of operation. A fine chain is attached at one end to a point on the beam near the fulcrum, the other end being attached to a slider which can be moved vertically (by means of a mechanism operated by a small handle outside the balance case), up and down a vertical column, thus decreasing or increasing the amount of the chain weight supported by the beam. The column is graduated so that the position

of the slider indicates the equivalent weight in the scale pan, and the slider is provided with a vernier. All weighings from 0.1 to 0.0001 gr. are made by use of the chain. When this device is used in conjunction with a rider, the rider is used for weighings from 1 to 0.1 gr., hence no weights below 1 gr. are required.

Roberval Balance

A large proportion of weighing machines used for trade purposes in retail shops, and for many other purposes, make use of the principle invented by a Frenchman, Professor Roberval, in 1670. Such machines usually have the pans above the beam, thus eliminating possible obstruction due to the pan supports, but there is a loss of sensitiveness due to the friction at an increased number of pivots, usually six or seven in number.

Roberval's balance in its original form (Fig. XVIII. 2) consisted of two horizontal members of equal lengths each pivoted at its centre point, two vertical members of equal length being joined to the ends of the horizontal members, by pivots. To the mid-point of each vertical member a horizontal arm was attached and weights were applied to the arm. Balance between two equal weights was always established irrespective of the horizontal positions of the weights on the arms, apparently contradicting the principle of equilibrium of moments of forces (if the moments of the equal weights are taken about a line joining the central pivots). This phenomenon can be most easily explained by applying the principle of work. When the mechanism, with equal weights is deflected from the normal position, the vertical distances moved by the weights are equal, hence the work done by one weight equals the work done on the other (work being equal to the product of force and distance).

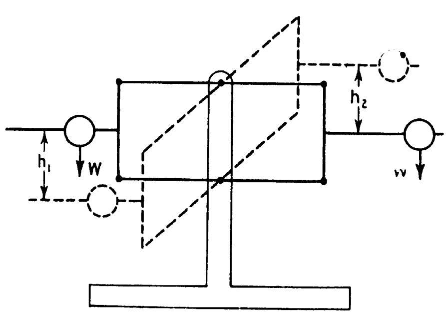


Fig. XVIII. 2. Original form of Roberval balance ($h_1 = h_2$ irrespective of horizontal positions of the equal weights).

There are many different ways in which the Roberval principle is adapted to weighing machines. Most commonly the top horizontal member is the beam, which must fulfil the same conditions as the beam of a balance. The lower horizontal member is called the stay and the side vertical members, or the legs, are continued above the beam and carry the pans. The beam and stay have fulcrum knife edges at their centres, and the legs make knife edge contact with the beam and stay. A load at any point in one pan will be balanced by an equal weight at any point on the other pan, if the beam and stay are parallel and their fulcra at their mid-points, and if the legs are both parallel to the line joining the beam and stay fulcra. If the stay is not parallel to the

beam the machine will weigh heavy or light according to the position of the load on the scale pan, and if the leg is not parallel to the line joining the fulcrum the sensitivity of the machine is affected by the position of the load on the scale pans.

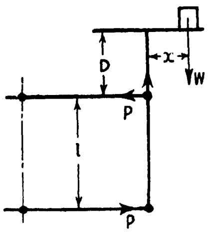


Fig. XVIII. 3. Roberval balance. Forces acting on leg.

By consideration of the forces acting on a leg (Fig. XVIII. 3) we get the relationship

$$W \times x = P \times l$$

$$\therefore \; P = \frac{W \times x}{l}$$

From this may be deduced the fact that the smaller the value of x, which is limited by the size of the pan, and the larger the value of l, the smaller will be the side thrust P on the knife edges tending to displace and wear them. Also D should be kept small for the sake of rigidity.

Having the load pans above the machine has several advantages but it is disadvantageous from the point of view of lifting heavy weights onto the pans. In the inverted or Imperial machine the pans are above the beam, but the legs and stay are also above the beam. The stay is in two parts but the Roberval principle holds provided that the four pivot points on each side form the corners of a parallelogram, and that the beam is pivoted at its centre.

The Beranger Balance

Certain notable features are embodied in the design and function of this machine (Fig. XVIII. 4). The motion of each scale pan is such

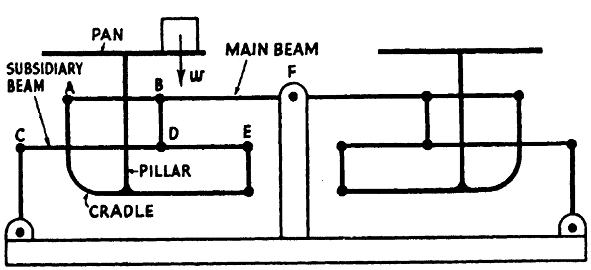


Fig. XVIII. 4. Beranger balance.

that the pan remains horizontal for any vertical displacement, and the application of a load not central to the scale pan does not affect the equilibrium of the balance. By the use of subsidiary beams and links the load is transmitted vertically to the main beam, hence there are no lateral thrusts on the knife edges. The pans are above the beam and mechanism.

Due to a weight w on a pan, let the vertical downward forces at the points A and E be w_a and w_e. The vertical downward force on the main beam at B, resulting from w_e is $w_e \times \frac{CE}{CD}$ (found by taking moments about C). The equivalent downward force at A due to $w_e. \frac{CE}{CD}$ at B, is $w_e. \frac{CE}{CD} . \frac{FB}{FA}$ which is equal to w_e when $\frac{CE}{CD} = \frac{FA}{FB}$. Hence when this condition is fulfilled the total equivalent downward force at A is $w_a + w_e = w$.

The Steelyard

The steelyard is an unequal armed balance, and operates on the principle of a lever of the first order. The beam is supported by means of a shackle which bears on the fulcrum knife edge. The load knife edge is a fixed distance from the fulcrum, the load being supported by a hook and shackle. The load is balanced by a movable counterpoise which operates along the long arm. When a load is applied the counter-poise is moved along the beam until the lever becomes steady in a horizontal position, then the position of the counterpoise indicates the load,

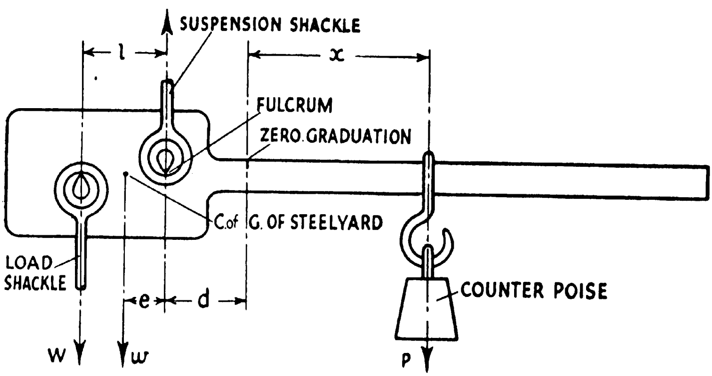


Fig. XVIII. 5. Steelyard.

or which purpose the long arm must carry a scale graduated so that he load may be read off directly from it. It is advisable that balance :an be established by a certain position of the counterpoise, when the oad is zero. This will be possible if the moment of the counterpoise is)alanced by the moment of the weight of the steelyard about the fulcrum ; ınd the position of the counterpoise will then be called the zero graduation.

W = load being weighed.
l = fixed distance between load knife edge and fulcrum knife edge.
w = weight of the steelyard with load shackle and hook but excluding the counterpoise.

e = the distance of the centre of gravity of the steelyard, etc., from the fulcrum.
d = the distance of the zero graduation from the fulcrum.
P = the weight of the counterpoise.
x = the distance of the counterpoise from the zero graduation when balance is established.

By taking moments of the forces about the fulcrum,

$$W.l + W.e = P(x + d)$$
$$= Px + Pd$$

And if $P.d$ is made equal to $w.e$

then $$W.l = P.x$$

$$\therefore W = \frac{P.x.}{l}$$

Hence the zero graduation is made at a position satisfying the condition stated above, the load then being proportional to the distance of the counterpoise from the zero graduation and the beam scale can be graduated to read directly in units of load weight. An adjustable balance weight is provided so that balance can be established with no load when the counterpoise is on the zero graduation.

Another type of steelyard provides variable counterpoise weights always situated at a fixed distance from the fulcrum. Using the equation derived above, $x + d$ is this fixed distance.

$$Wl + w.e. = P(x + d)$$

$$\therefore W = \frac{P(x + d) - w.e.}{l}$$

Thus for W to be proportional to P which might be advisable, the centre of gravity of the beam should coincide with the fulcrum, which would reduce the term $w.e.$ to zero.

The two types described can be combined, the counterpoise weights in the fixed position (at the end of the beam) being used to measure certain units of load, and the sliding counterpoise to measure subdivisions of one unit.

The steelyard is frequently incorporated in platform weighing machines, weighbridges and tensile and torsion testing machines.

Platform Machines and Weighbridges

These machines are commonly used for weighing heavy loads, and consist of a platform close to the floor level, supported on a system of compound levers terminating in a tension rod and shackle connected to the load knife edge of a steelyard. It is essential that the true weight will be indicated irrespective of the position of the load on the platform, and also that the load platform when depressed remains horizontal. The principle of the Beranger balance is utilised for this purpose.

Self-Indicating Weighing Machines

The operation of balancing a load by means of standard weights or by the positioning of a counterpoise is eliminated by the use of these machines in which the load is indicated by a movable pointer on a

graduated scale. Such machines are very widely used for purposes where the highest degree of accuracy is not required, as for counter machines, platform machines and the load indicating unit of testing machines.

The load pan is attached to a lever mechanism terminating in a tension rod coupled to the end of one of the arms of a bell crank lever. At the end of the other arm is a heavy mass which is raised when the tension rod exerts a downward pull, and a position of equilibrium is attained when the moment of the pull equals the moment of the pendulous arm about the lever pivot, i.e. when $P.l = Wx$ (Fig. XVIII. 6). A pointer is attached to the lever which indicates the angular movement of the lever on a scale. In the simplest form of this machine the scale is not linear, i.e., equal load increments are not indicated by equal scale divisions.

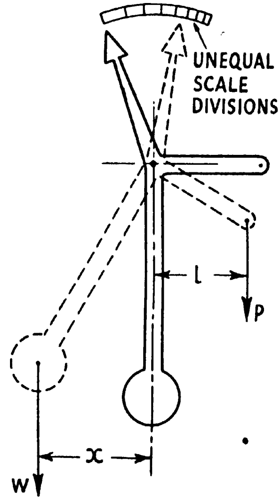


Fig. XVIII. 6.
Self-indicating weighing machine.

Equal scale divisions for equal load increments can be obtained by making the tension rod in the form of a flexible metal strip which operates on the periphery of a cam (Fig. XVIII. 7) so designed that the variable moment which it produces compensates for the variable moment arm of the pendulum.

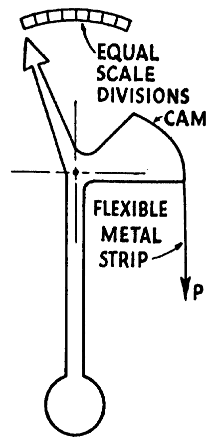


Fig. XVIII. 7.
Self-indicating weighing machine.

Spring Balance

The extension of a helical wire spring is proportional to the load producing it, provided, of course, that the wire is not stressed beyond its elastic limit, and a spring balance consists of a simple means of indicating the extension on a scale which is suitably graduated so that the load producing the extension may be read directly from it.

Pocket and tubular balances use a single spring and indicate the load directly on a linear scale. Circular balances use springs in pairs, from one to four pairs according to the load capacity. In a circular balance with one pair of springs (Fig. XVIII. 8) a yoke fixed to the balance frame is connected across the tops of the springs. Another yoke, which carries the load fixture, is connected

across the lower ends of the springs and is free to move when the springs elongate. A rack which is attached to the bottom yoke actuates a pinion connected to the pointer spindle, which rotates as the springs extend. The rack is not rigidly connected to the bottom yoke, but is pivoted at one point, and a small spring presses the rack into contact with the pinion. This arrangement ensures contact and eliminates errors due to backlash and imperfect setting of the rack and pinion.

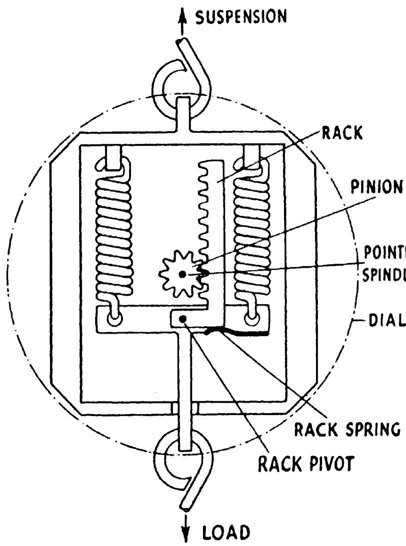


Fig. XVIII. 8. Circular spring balance mechanism

SECTION 3

NAVIGATIONAL AND SURVEYING INSTRUMENTS

CHAPTER XIX

BAROMETER, BAROGRAPH AND ALTIMETER

The barometer is an instrument for measuring the weight of the air or atmospheric pressure, which varies within certain limits from place to place at a given time and from time to time at a given place. Knowledge of these variations is the most important of several factors in the science of weather forecasting and has several other practical applications such as indicating the height of a place or thing—e.g. aircraft—above sea-level or depth below sea-level, as in mines.

That the atmosphere has weight and exerts a pressure was first definitely proved by Galileo in the early 17th-century and his pupil Torricelli (1608-1647) was the first to make a barometer. Between them these two Italian scientists exploded many strange ancient ideas about the atmosphere and its nature.

The basic principle of the barometer is to balance against the weight of the atmosphere a column of liquid of known weight in a tube sealed at the top to provide an empty space—a vacuum—above the liquid while the base of the tube is open to the air pressure so that this may bear against the lower surface of the liquid and support the weight of the column. To provide this lower surface the bottom end of the tube may be turned upwards in a U-shape, but the details of barometer construction are described later.

Changes in the air pressure are indicated by changes in the level of the liquid at the top of the tube and means are provided for measuring these changes by a scale graduated in inches (in.), millimeters (mm.) or millibars (mb.) alongside the part of the tube through which the top surface of the liquid may be expected to vary. Normally the tube is mounted vertically, though this is a matter of convenience rather than essential.

As will be described later, the liquid and the tube may be replaced by a mechanical device which expands or contracts under varying air pressure, e.g. an arrangement of sealed metal bellows which open or close as the air pressure decreases or increases. When this arrangement is used, in what is known as the aneroid barometer, the scale to indicate the height of liquid is replaced by a light metal arm connected at one end to the bellows and at its other end to a pointer which moves over a scale or dial. This may be graduated in inches or millimetres to give an equivalent reading to the liquid type of barometer or it may be graduated in feet to indicate directly the height of the place where readings are taken, in which case this barometer becomes an altimeter.

Choice of Liquid for Barometer. The liquid generally used for barometers is mercury, on account of its high density (13.596 gm./ml. at 0° C.) and very low vapour pressure; it is also opaque. If water were used, the barometer would have to be over 34 feet in length If glycerin (1.26 sp. gr.) is used the barometer would be over 27 ft. long The only advantage gained by using lighter liquids is the great alteration in the level of the liquid for a small change in pressure. J. B. Jordan designed a glycerin barometer in 1873.

Barometers

The two main types of standard mercurial barometer in use in this country are the Fortin and Kew patterns. In the Fortin type (Fig. XIX. 1) arrangement is made for raising and lowering the level of the mercury in the cistern to the fixed datum point in the cistern. This avoids moving the scale, which measures the height of the barometer column. The mercury can also be raised so as to fill the tube, thus making the barometer portable. The fixed datum point in the cistern is an ivory pointer the tip of which coincides with the zero of the scale. When a reading is taken the level of the mercury is adjusted so that it is just in contact with the ivory point; the zero of the scale is then on the mercury surface. The length of the mercury column is read by a vernier which is moved over the graduated scale by a rack and pinion. The scale is graduated in inches and centimetres, and can be read to an accuracy of 0.002 in. or 0.05 mm. Attached to the instrument is a thermometer, as the observed height must be corrected for scale errors, temperature, latitude and reduction to sea-level. How this correction is made will be described later.

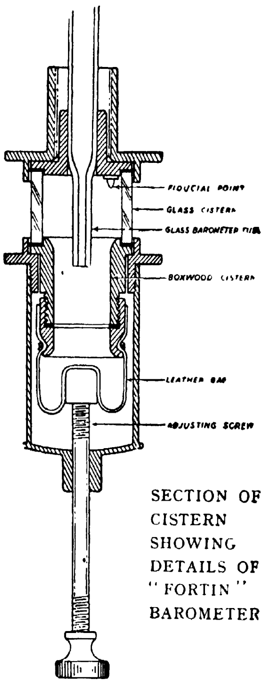


Fig. XIX. 1. Standard Fortin barometer. Section of cistern showing details for adjusting level of mercury in cistern.

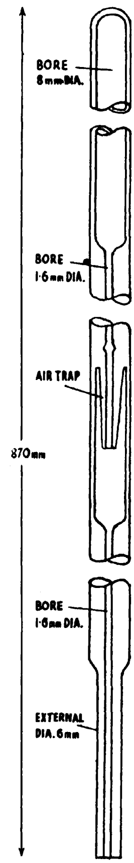


Fig. XIX. 2. Kew pattern station barometer tube showing narrow bore of tube and air trap.

The length of the graduated scale depends upon where the barometer is to be used. If the barometer is to be used in a mine, the upper limit must be increased. If it is to be used for high altitude surveying, the scale must be graduated down to 18 or even 15 inches—this corresponds to approximately 20,000 ft. altitude. since a difference of one inch of mercury corresponds to a rise or fall of 900 ft. at ground level and to 1,350 ft. at 11,000 ft. altitude.

The Kew Pattern Station Barometer. This type is constructed on similar lines to the Fortin, but differs from it in three essential points, (1) the barometer tube has a narrow bore for most of its length (Fig. XIX. 2),

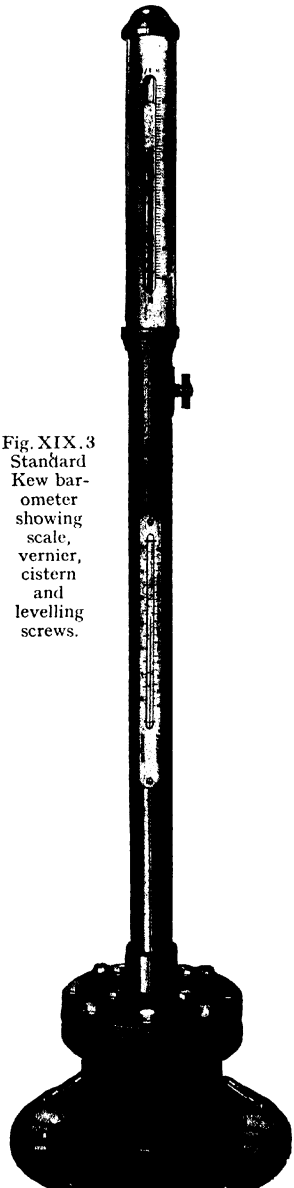


Fig. XIX. 3 Standard Kew barometer showing scale, vernier, cistern and levelling screws.

(2) the scale is fixed (Fig. XIX. 3), and (3) in having a cistern which is made of steel, (Fig. XIX. 3). It is also provided with an air trap in the form of an inverted pipette (Fig. XIX. 2), which collects any air from the cistern and prevents it from passing into the vacuum space above. The scale on this type of barometer is different from that on the Fortin. The Fortin depends upon a double setting of the scale to give the atmospheric pressure. This procedure is shortened in the case of the Kew pattern which is adjusted by a single setting of the vernier (Fig. XIX. 3). The scale is a uniformly contracted one, to compensate for the lack of adjustment made in the mercury level in the cistern by means of the fiducial point. This is called "compensation for capacity." In practice the amount of contraction depends upon the internal diameter of the barometer tube, the internal diameter of the cistern, and to a lesser extent on the external diameter of the piece of tube dipping into the mercury. If the cistern diameter is made five times that of the tube, the scale contraction is 0.96 approximately, that is to say a nominal inch measures 0.96 true inch. If greater accuracy be required, the ratio of cistern diameter to tube must be increased.

Marine Barometers. Many types of marine barometers have been designed and discarded for one reason or

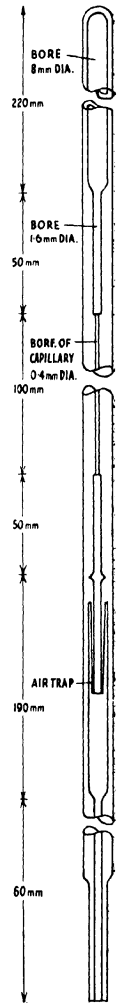


Fig. XIX. 4. Kew type marine barometer tube showing section of capillary tubing to prevent "pumping" and air trap.

another. The most interesting of these is perhaps the conical barometer, made by Amontons in 1695. It consisted of a conical tube closed at the top and open below, the diameter gradually increasing from the top to the bottom, variations in pressure causing the mercury to rise and fall in the cone. The one in use at the present time is the Kew Pattern Marine Barometer. In its present form it is similar to the station pattern (Fig. XIX. 3) except that it has a section of capillary tubing (Fig. XIX. 4) inserted above the air trap, so that the movement of the mercury is damped. This oscillation of the mercury is technically called "pumping." When the barometer is used for meteorological purposes, the specification requires that the damping is such that it takes from six to nine minutes for the barometer to record the actual barometric pressure after having been made to register from between 15 and 18 mb. above this pressure. The scale, etc., is the same as on the Kew station barometer.

The Gauge Barometer. This instrument has a wider sphere of use than any so far described, though it differs from them only in detail, and can be put in connection with any artificial gas pressure that it is necessary to measure. It may be of the cistern type or siphon type. When the cistern type is used, the cistern is made airtight and it is fitted with a cock for connection to the pressure that is to be measured. The siphon type of gauge barometer is less accurate than the cistern type.

Correction of Mercury Barometer Readings to Standard Conditions. The reading of a mercury barometer is influenced by changes of temperature and of gravity acting upon the mercury, so the reading must be reduced to standard conditions. It should be noted that there is a fundamental difference between temperature correction for a Fortin and a Kew type barometer, though this difference is relatively small. There is also a slight difference in the formula for temperature when the scale is graduated in inches from that when the scale is graduated in millimetres. In the Fortin and siphon barometer the scale is graduated in true linear measure, uncontracted. The temperature coefficient involves two quantities, (1) the coefficient of expansion for mercury and (2) the coefficient of expansion for the scale. When the barometer is graduated in millimetres, the scale is considered standard at 0° C., while if the scale is graduated in inches, the scale is considered standard at 32° F., so the mercury has to be corrected to the standard temperature.

For the Fortin and siphon barometers the correction to be applied in order to obtain true millimetres of mercury at 0° C. is

$$H_t - H_o = \frac{t\,(\beta - \alpha)\,H_t}{1 + \beta_t}$$

When the barometer is graduated in inches the correction to be applied in order to obtain true inches of mercury at 32° F. is

$$H_t - H_o = \frac{[(t - 32)\,(\beta - \alpha) + 30\alpha]\,H_t}{1 + (t - 32)\beta}$$

where H_o is the true barometric height at 0° C. or 32° F.

H_t is the barometric height at temperature t° C. or t° F.

α is the coefficient of linear expansion of the scale.

β is the coefficient of cubical expansion of mercury.

In the case of the Kew barometer the above temperature coefficient can

be used as a first approximation. If a more accurate correction is required the reader should consult a standard book of reference on the subject.

Correction of the Barometer for Gravity. Standard gravity is the value of gravity at mean sea-level in latitude 45°. The height of mercury column varies inversely as the value of gravity at the station where the barometer is read. For precision work the value of gravity at the station must be known and as this is practically impossible in many cases, especially at sea, the following formula is generally used :—

$G_O = G_{45}\ (1 - 0.00259 \cos 2\lambda)$.

$G_H = G_O\ (1 - 0.000000597 \times H)$. If H is measured in feet.

$G_H = G_O\ (1 - 0.000000196 \times H)$. If H is measured in metres.

where G_O is the gravity at sea-level in latitude λ.

G_{45} is standard gravity.

G_H is the gravity at height H above sea-level in latitude λ.

The Aneroid Barometer

This, as its name implies, is a non-liquid barometer which was invented by Lucius Vidi in 1843. The modern aneroid barometer is an instrument of high precision and is nearly as accurate as the mercurial barometer. It has the advantage of being able to be used where a mercurial barometer is not admissible, for example on aircraft. The general principle of this instrument is the fact that a thin metal disc responds elastically, to an appreciable degree, to the difference of pressure on its faces.

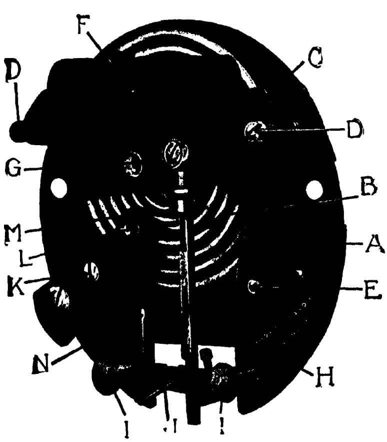


Fig. XIX. 5. Construction of an aneroid barometer movement.

A. Base plate.
B. Corrugated vacuum chamber of nickel silver, from which all air is exhausted.
C. Bridge which spans vacuum chamber B.
D-D. Adjusting screws, for altering tension on chamber B.
E. Adjusting screw which raises bridge C up or down.
F. Steel spring sliding in bridge C.
G. Knife-edge.
H. Bar or arm, compensated for temperature which at its end magnifies movement of spring F.
I-I. Two support pillars, fitted to plate A.
J. Bar or regulator, set between and working on steel points, or pivots, passing through supports I-I.
K. Arm or cock.
L. Pin or arbor, passing through end of cock K.
M. Hairspring, fitted to pin L
N. Chain of steel, one end of which is fitted to arm passing upward from regulator L, the other end being secured to pin L to which the indicating hand is fitted

The general construction of the instrument is shown in Fig. XIX. 5. The vacuum chamber is usually made of thin sheet, nickel-silver alloy or hardened and tempered steel (see Fig. XIX. 6). In the most modern type where hardened and tempered steel is used, a number of diaphragms are formed into one complete unit. The chamber is exhausted of air and the diaphragms are corrugated in order to produce greater flexibility. The method of transferring the movement of the diaphragm to the dial of the instrument is by a suitable system of magnifying levers.

The relation between the amount of movement of the centre of the diaphragm and the pressure change which causes the movement, is very nearly linear. For pressure change from 15 to 31 in. of mercury, a magnification of the order of 200 can be obtained. Changes in temperature affect the accuracy of the aneroid and have to be allowed for. The thermal expansion of the mechanism introduces a small error, but the main error is due to the change in the value of the elastic moduli of the material of the vacuum chamber system due to temperature changes. Two methods are adopted to compensate the aneroid for temperature changes. One is to make the long arm of the lever system of two different metals, viz. brass and iron brazed together. With this method the vacuum chamber must be thoroughly exhausted. The other is to suitably proportion the volume of the space inside the vacuum chamber when closed to that when open, and by leaving a definite amount of dry air in the chamber. The modern aneroid with the improved method of construction of the vacuum chamber and its mechanism is an instrument which over its whole range has practically perfect compensation for temperature and other errors. Fig. XIX. 7 illustrates one of these precision aneroid

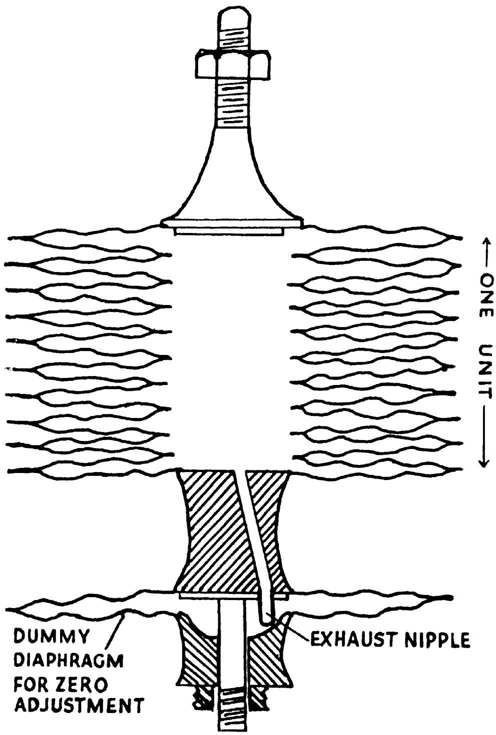


Fig. XIX. 6. Vacuum chamber unit, showing number of diaphragms built up to form unit.

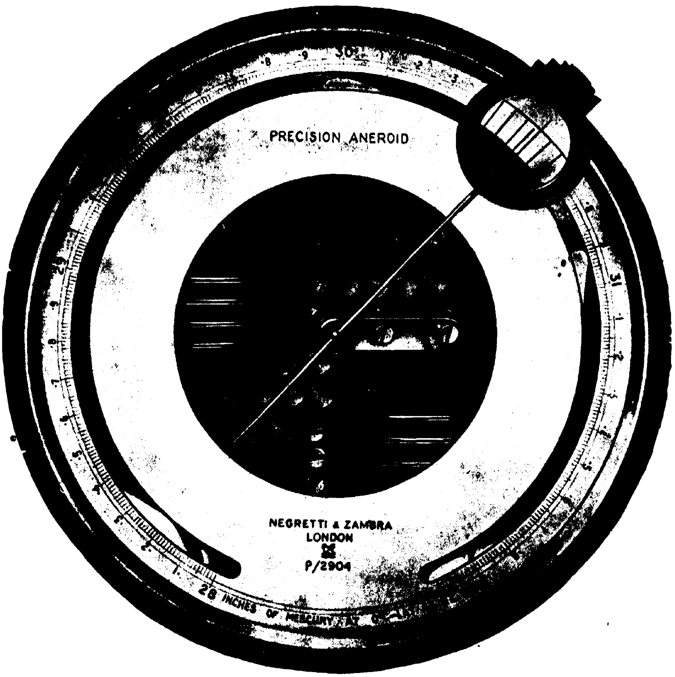


Fig. XIX. 7. Precision aneroid barometer, showing scale, knife edge pointer, anti-parallax mirror and magnifying lens.

barometers. For the range 28 to 31 in. the scale is divided to 0.01 in. In the 21 to 31 in. range, the scale is divided to 0.02 in., and it is therefore possible to estimate pressure to 0.001 in.

The Aneroid Barograph. This instrument is a self-recording barometer, which is generally used for meteorological purposes where a continuous record of the variation in pressure is required (see Fig. XIX. 8). It is also used for certain work in the field of aeronautics. The principle of the instrument is the same as that of the aneroid barometer, except that the metallic chain operating the indicating needle is replaced by a long pen which traces out the record on a

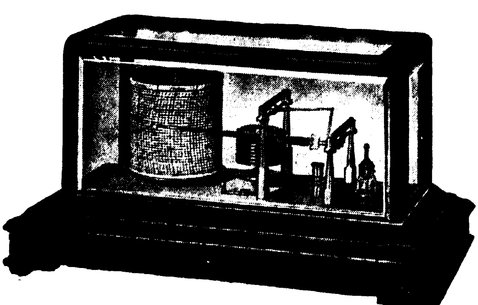


Fig. XIX. 8. Recording barometer.

uniformly revolving drum driven by clockwork. The accuracy of this instrument is not quite as good as that of the aneroid owing to the friction of the pen on the paper, and other errors.

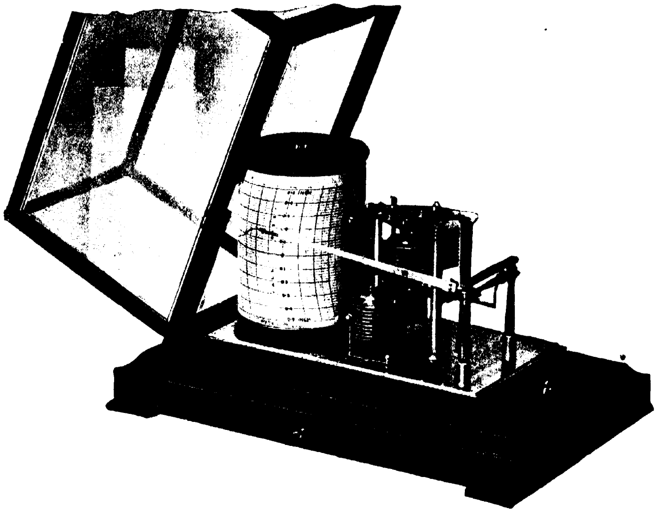


Fig. XIX. 9. Precision recording barometer or micro-barograph.

The Micro-Barograph is an instrument with a higher degree of sensitivity (Fig. XIX. 9). This is a refined development of the barograph. In this instrument the chart is figured and divided to read to 0.02 in. of mercury pressure. The records are on a much larger scale than in the barograph.

Altimeters

These instruments are chiefly used to measure the height of an aircraft above the ground level and they are also used in surveying. They are very similar in principle and construction to the aneroid barometer, the main difference being in the arrangement of the mechanism. They actually measure atmospheric pressure, but since atmospheric pressure varies with altitude in a known manner, the instrument is graduated in feet of altitude.

The main component of the altimeter, as of the aneroid barometer, is the vacuum chamber. The mechanism for transferring the movement of the diaphragm to the scale is illustrated in Fig. XIX. 10. This type of instrument is known as the K.B.B.-Kollsman. The movement of the diaphragm is transferred to the pointer by means of a rocking shaft assembly, calibration arm, sector and multiplying gear train. In order to reduce backlash a hairspring is fixed to a member of the gear train and anchored to the mechanism plate. Another important feature of this instrument is the compensating bracket which forms part of the

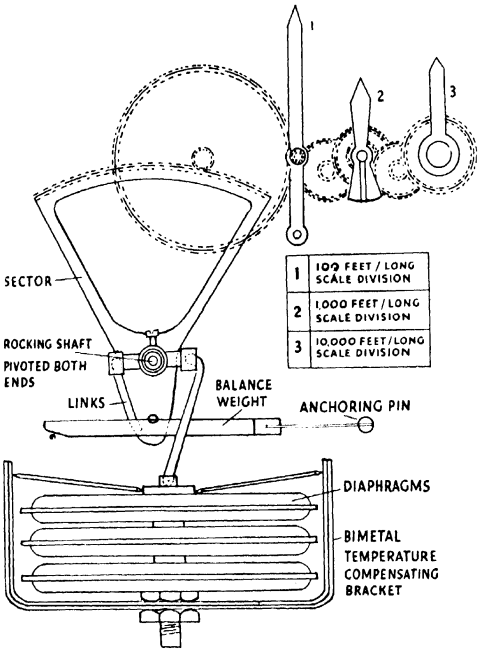


Fig. XIX. 10. K.B.B.-Kollsman sensitive altimeter.

diaphragm assembly, this element reducing to a minimum the errors due to temperature variation. A further refinement is the balance weight which maintains perfect balance in all positions of the diaphragm and mechanism. The whole of the mechanism is housed in an airtight case, and connection to the static line is by means of a nipple.

Another type of precision altimeter, the movement of which is illustrated in Fig. XIX. 11, differs from the one previously described in the arrangement of the vacuum chamber. The movement consists of two sets of four exhausted vacuum chambers. These are connected to the frame of the instrument and the free ends are connected by means of flexing strips to a magnifying lever of girder construction. The two sets are balanced. The fulcrum of the lever is formed by a flexing strip of stainless steel. Through a system of levers the movement of the end of the lever is magnified and transmitted to a chain and pulley mechanism which operates the pointer, the chain being kept in tension by means of a hair spring. This instrument is compensated for temperature by suitably proportioning the volume of the space inside

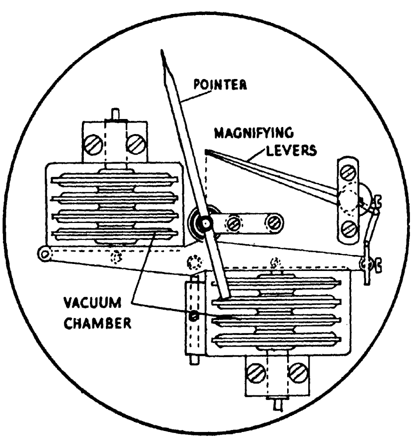


Fig. XIX. 11. Precision aneroid barometer movement.

the vacuum chambers when closed to that when open, and by leaving a definite amount of dry air in the chambers. This and the improved method of construction give practically perfect compensation for temperature over the whole range of the instrument.

Principle of Calibration. The calibration of an altimeter depends upon a law connecting the pressure and height. Several laws are in use. The first to be adopted in this country was that given by the late Sir George Airy in 1867. It is known as the Airy's Table. This table has a range of height of 0 to 12,000 feet, and assumes a mean atmospheric temperature of 50° F. between any two given heights. The basis of the scale can be shown to be the formula

$$h_2 - h_1 = 62759 \times log_{10} \frac{p_1}{p_2}$$

The scale makes allowance for the moisture content of the atmosphere and is still used for graduating surveying altimeters. The scale used for British altimeters is the International Commission for Air Navigation, I.C.A.N. This assumes that the temperature falls uniformly at the rate of 1.98° C. per 1,000 ft. from 15° C. at ground level to —56.5° C. at 36,000 ft.; above this height it is supposed to remain constant at —56.5° C. This law is expressed by the equations

$$\frac{P}{P_0} = \left(1 - \frac{1.98H}{288}\right)^{5.356} \text{ for heights up to 36,090 feet,}$$

and $\mathrm{H} - 36{,}090 = 47{,}000 \log_{10} \frac{P_1}{P}$ feet, for heights greater than 36,090 feet.

P_0 = ground pressure in millibars (taken as 1013.2 millibars).
P = pressure at height H in millibars.
H = height in thousands of feet.
P_1 = the pressure at 36,090 ft. calculated from the second equation.

Another method is the Isothermal Convention. This assumes the temperature to be constant 10° C. at all heights and that the pressure varies with the height. The formula connecting these two is

$$H = 62{,}580\ log_{10} \frac{P_0}{P} \text{ where } P = \text{pressure at height } H.$$

P_0 = ground pressure in millibars (1013.2 millibars).
H = height in thousands of feet.

From these formulæ tables can be drawn up connecting pressure and height.

It is desirable to emphasise that the altimeter has limitations as a height measurer. It is calibrated for average conditions of atmospheric pressure and is subjected to errors if used under any other. If set for zero at sea-level, it will give reasonably accurate results during flight if there is no change in atmospheric pressure during the flight. Nevertheless, with these limitations the instrument has the great advantage of giving, with some lag, the reading of height above ground.

CHAPTER XX

GYROSCOPIC INSTRUMENTS

Any wheel rotating at a high speed round a fixed centre serves to illustrate the principle of gyroscopic inertia, i.e. the tendency of such a wheel to maintain whatever position in space that it occupies when it acquires its motion. Practically all gyroscopes consist of a wheel with a heavy rim, the ends of the axle of which are mounted in a ring which, in turn, is mounted in another ring, so that the two pairs of mountings are at right angles to each other. This means that the wheel has three degrees of freedom, i.e. it can move in three dimensions or directions while its centre point remains stationary; it may rotate on its axle, the ring in which the axle is mounted may be turned in its own mounting, and the outer ring may similarly be turned in its mounting on some kind of stand, so that when not rotating the wheel may be moved to any desired position which, if the balance is correct, it will retain. If in any given position the wheel be given a high speed of rotation, it will maintain this position against considerable disturbing force; the actual amount of force required to disturb the direction of the wheel's axle depending on three things—the speed of rotation of the wheel, its weight, and diameter. A good illustration is a bicycle wheel of which the spindle is held in each hand while a second person spins the wheel rapidly; any attempt on the part of the one holding the wheel to alter its plane of rotation meets with considerable resistance.

Fig XX. 1. A model gyroscope used to illustrate principles and functioning. If a force (torque) be applied as at T, the gyroscope axle will move (precess) in the direction P.

Gyroscope wheels or rotors, as they are called, applied practically vary in size and weight from a few inches and ounces to several feet and up to as much as 100 tons; their speeds of rotation range from 800 r.p.m., for the very largest rotors, up to 27,000 or more r.p.m. for small motors.

Theory

The underlying principle of the gyroscope is the conservation of angular momentum—any object set spinning, whether it be a small wheel weighing only a few ounces or the earth, will, once it is given rotation, maintain that rotation and the direction of the axis of rotation so long as no disturbing factor is introduced. If a disturbing factor is introduced, its effect on the gyroscope is not what might be expected; instead of disturbing it in the direction in which the

force is applied, the reaction will be at right angles to this force, so that in Fig. XX.1 if a force be applied as at T the effect will be to deflect the gyroscope in the direction P at a speed proportional to the applied force. This is known as precession, and the conservation of angular momentum and precession are the two fundamental principles at the basis of gyroscopic applications. If a gyroscope could be made entirely free from friction and were given an initial rotating impulse at sufficient speed, it would retain its position, or rather direction, indefinitely.

The first practical application of the gyroscope was indeed an application or deduction from this fact. It was used by Foucault in 1852 to demonstrate the rotation of the earth. A gyroscope made as perfectly as was then possible being spun at high speed would apparently change its position through the twenty-four hours of the day. Actually the gyroscope maintained its direction, but the rotation of the earth—taking with it all the objects round the gyroscope—made it appear that the gyroscope was altering its direction, whereas it was the surrounding objects and not the gyroscope that moved.

Unfortunately, an entirely frictionless gyroscope is practically an impossibility, although in recent years much research has been devoted and is being devoted to the development of bearings as free from friction and as hard wearing as possible. Nevertheless there is always some friction which has the effect of causing precession (and possibly oscillation according to the conditions of suspension) in any gyroscope. The means adopted either for reducing this to a minimum or for turning it to practical effect, are highly ingenious or elaborate in some of the instrument applications for which the gyroscope is now used, and this has been accompanied by important developments in the methods of driving the rotor, so that if Foucault could see some of the modern applications, he would certainly be very impressed by the development of his little toy.

It may perhaps be useful to point out at this stage that the toy gyroscope that could be bought for a few pence should more accurately be referred to as a gyroscopic top, because although it could do a large number of entertaining tricks, it was seldom mounted in a frame or frames that gave it three degrees of freedom.

Practical Applications

Perhaps the first attempt to apply the gyroscope practically was on the two-wheeled or monorail car, a motor car running on two wheels only (fore and aft) on the roads, or a rail car mounted on a single rail. The pioneer of these developments was, of course, Brennan and he certainly succeeded in producing a vehicle that would run, though its excessive weight and other limitations meant that it was no practical competitor to the ordinary four-wheeled vehicle. There are, however, certain advantages, and there are some quite knowledgeable people who firmly believe that in another century or so the majority of our railway trains will be monorail cars balanced by a gyroscope, though it is perhaps safer to say that this anticipation is largely a matter of opinion—which is sharply divided.

It was in the early years of the twentieth century that the possibility of an adaptation of a gyroscope to replace the magnetic compass began to be investigated, and in 1908 Dr. Hermann Anschutz Kempfe patented

his gyro-compass—to be followed by Dr. Elmer A. Sperry in the U.S.A. three years later, while Mr. S. G. Brown—in conjunction with Professor John Perry—produced the first English gyro-compass in 1916. From these early experiments the history of the gyroscope compass has been one of continual development, and now it represents some of the most ingenious and highest precision engineering to be found anywhere. In all cases the aim of the designer has been to eliminate friction both in the rotor bearings and in the mounting of the rotor frames, and to provide a reliable means of drive—generally electric.

Perhaps one of the best known early applications of the gyroscope is that in the torpedo where the gyroscope is used to provide directional control, and it may also be a surprise to know that so long ago as 1911 an attempt was made to apply gyroscopic stabilisation to an aeroplane.

The possibility of gyroscope stabilisation of ships has long been a favourite subject with gyro engineers and, of course, it has been applied with a considerable amount of success, although there are still differences of opinion as to whether it will ever become general even on ships where stabilisation would be a very valuable asset.

It is also general knowledge that the modern big aircraft could not do its present work—especially its war work—without its gyroscopes, which are used for purposes so various as providing navigating instruments, stabilising gun platforms, bomb sights and cameras, and piloting the whole aircraft. Auto-piloting both of aircraft and of ships, is, indeed, perhaps the most important of all modern applications because the mechanical pilot is so much more sensitive and tireless than its human counterpart. One practical effect of automatic gyroscopic control of both aircraft and ships is a considerable saving in fuel by the steering of a far more accurate course than a human pilot could hope to attain.

Obviously with such a wide range of applications it is impossible to do more here than give a very brief survey of some of them, and those selected are the gyroscopic compass for ships (this type of compass is not applicable to aircraft), ship stabilisation, the auto-pilot for both ships and aircraft, and the gyroscope in the torpedo.

Gyro Compass

If a gyroscope is set spinning with its axle horizontal (i.e., parallel to the earth's surface) it will at any point except at either of the two poles, show the rotation of the earth by a continual change in the angle made by its axle to the earth's surface (unless the axle is pointing due north and south). As has already been stated, it is in point of fact the earth's surface that changes its angle and not the gyroscope, assuming this to be free from frictional interference. If, therefore, a weight be attached to the gyroscope making it pendulous, this weight, attracted to the centre of the earth by gravity, will exercise a torque on the gyro which will cause precession, and the effect of the precession will be that the gyroscope will tend to swing into the plane of the meridian, i.e. north and south.

On reaching the true meridian, however, the pendulous gyroscope will swing past this and will then return, oscillating about the meridian, unless the oscillations are damped. This is the fundamental principle of the gyro-compass, but there are obviously many objections to a compass

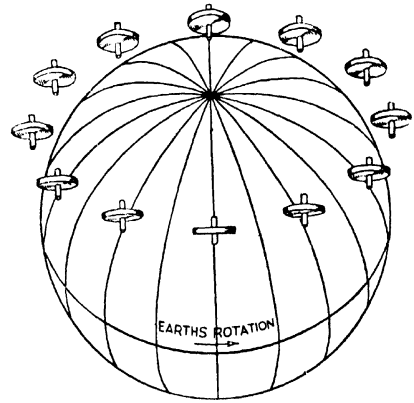


Fig. XX. 2. How a gyroscope tends to maintain a constant direction in space although mounted on the rotating earth and illustrating the functioning of the gyro compass.

that will swing backwards and forwards across the meridian over a considerable period of time, and the practical design of the gyro-compass is directed to eliminate these faults which would arise with a simple gyroscope that one attempted to use as a compass (see Fig. XX. 2).

First, the axle of the gyroscope must be maintained horizontally or very nearly so, or otherwise it it will only give a satisfactory reading by being projected on to a horizontal surface which would involve quite unnecessary and avoidable complication. Second, the impossibility of eliminating friction from bearings means that the gyroscope itself will be subjected to torques other than that due to its pendulosity, and so long as friction cannot be eliminated, some compensation for these undesired torques must be introduced.

Of the various methods adopted—all of which reduce to attempts to insulate the gyro and its mounting from frictional contact—perhaps that used in the Anschutz compass is the most ingenious. In this the gyro is mounted in a hermetically sealed sphere which is floated in another sphere containing liquid, i.e. one sphere is located inside another and the intervening space is filled with liquid of such a density as to maintain the inner sphere just floating. Further, the liquid (which was originally mercury) is acidulated water which acts as a conductor of electric current used to drive the rotor—the liquid thus acts as a friction insulating material and also as a vital part of an electrical circuit. In the Sperry gyro-compass the sensitive element, i.e., the element containing the rotor and bearings, is suspended by a torsionless wire from the surrounding unit known as the phantom unit. In the Brown gyro-compass the sensitive element is supported on a fluid column that pulsates three times a second, so that the whole sensitive element is constantly moving up and down through a range of about one-eighth of an inch. In the Anschutz compass the pendulous effect is derived from weighting the base of the inner sphere. In the Sperry it is achieved by what is called the mercury ballistic—this consists of two reservoirs of mercury, one on either side of the sensitive element and connected by a small bore tube. As soon as the gyro tends to tilt in one direction, the mercury is transferred from one tube to the other and so causes the effect of pendulosity—i.e., the action of gravity—providing the meridian seeking torque. In the Brown compass the gyro container is maintained horizontal by the operation of air pressure on cylinders partly filled with

oil. As the gyro tends to tilt, a valve is opened directing an air stream on to the appropriate oil surface, so increasing the pressure on it and doing the work of the mercury ballistic in the Sperry compass.

The reading of a gyro-compass may be taken directly from degrees marked round the rim of a convenient element, and compared with a lubber line in the outside mounting which is aligned with the fore-and-aft axis of the ship. It is, however, common practice for a gyro-compass to be mounted below decks and for its reading to be taken through a transmission system to distant dials located at convenient points, e.g., on the bridge for the helmsman.

By way of comparison of the three principal types of gyro-compasses, it may be said that the rotor of the Sperry weighs 52 lb., rotating at 6,000 r.p.m.; that of the Brown weighs 4½ lb., rotating at 14,000 r.p.m.; and that of the Anschutz weighs approximately 5 lb., rotating at 20,000 r.p.m. In all cases the rotor itself constitutes the rotating unit of a squirrel-cage alternating motor. Another conspicuous difference is that whereas the Sperry and the Brown both have a single gyroscope, the Anschutz has two, these being set at an angle of 45° to the north-south line. At one period of its development the Anschutz compass had three gyros—the third being used for stabilisation, but this has now been discarded and all gyro-compasses rely for stabilisation, i.e., insulation from ship's movement, on ordinary gimbal mounting.

Once the gyro-compass became regular equipment for ships it was a matter of logical development to connect the compass more or less directly with the steering gear, so that when a course was set the compass would not only indicate it but would steer the ship, and now this auto-pilot system is rapidly gaining ground afloat as it has in the air. The method of interconnecting gyro and steering gear is such that as the gyro-compass indicates the ship's deviation of course of more than ⅓ of a degree, an electric contact operates a hydraulic valve controlling the steering engine, so that an error of less than a degree is corrected immediately it develops, which is much more sensitive steering than any human pilot could hope to achieve.

Latitude, Speed and Course Errors

As the gyroscope is affected by latitude (at either pole the gyro ceases to indicate direction and in practice cannot be used as a compass in latitudes higher than 75°), correction for latitude is necessary in the application of all gyroscope compasses; combined with this is the error due to the travelling of the ship over the surface of a rotating earth. If the ship be moving due east or west the error is negligible and it is at a maximum when the ship is going due north or due south. In some gyro-compasses allowance for this error has to be made by a human supervisor, in others the error is automatically and mechanically corrected by the speed and course error device incorporated in the gyro itself. Thus, although the gyroscope has its own error which in one sense corresponds to the variation and deviation errors of the magnetic compass, the gyro, unlike the magnetic compass, can be made to provide its own corrections. The error due to the speed and course of a ship travelling due north or south (i.e., the maximum error) is approximately one degree for every ten knots of the ship's speed in about latitude 50°. On any

other course between N. or S. and E. or W. it is less, varying as the cosine of the course. With marine craft—for which thirty knots is a high speed—this means a maximum error of three degrees, which can easily be calculated and allowed for. With aircraft travelling at ten times this speed, the resultant error of thirty degrees is a very different proposition, and it is largely for this reason that the gyro-compass is not a practical instrument for use on aircraft. So far as one can say at the moment, not only is it never so used, but it never will be so used, although there are, of course, gyroscopic instruments on aircraft that, so far as possible, satisfy the function of a compass.

Ship Stabilisation

From what has been said of the rigidity of a gyroscope, it is apparent that if a large enough gyroscope were vertically mounted in a ship with the lower end of its axle fixed to the keel and the upper end to a strong deck beam, its effect would be to check rolling of the ship. In practice, the installation is a much more complicated affair, consisting of small sensitive gyros that may anticipate any rolling of the ship after its first movement and then control or precess large gyros that exert the anti-rolling moment. The gyroscopic effect must be accurately calculated for the ship in which the installation is to be made, it must take into account the ship's period of roll, and also the ship's metacentric height.

Gyroscopic stabilisation is employed on various craft where rolling needs to be reduced to the minimum possible degree, which does not necessarily mean the ship on which the comfort of passengers or crew is a supreme consideration. Thus, aircraft carriers probably see the widest application of gyroscopic stabilisation at the present time, but

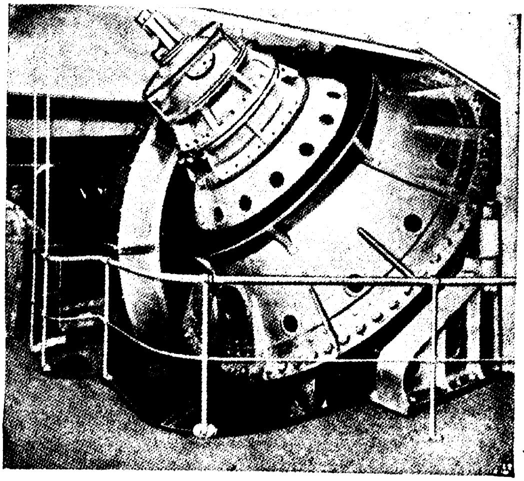


Fig. XX. 3. One of the three Sperry stabilising gyroscopes in the Italian liner *Conte da Savoia*. The rotor weighs 100 tons and spins at 800 r.p.m.

the only large passenger liner ever put into service with gyroscopic stabilisation was the Italian *Conte di Savoia*, in which the equipment weighed 660 tons, which was only 1⅓ per cent of the weight of the ship, and although there were three large gyroscopes they did not occupy space that could have been devoted to any other useful purpose (Fig. XX. 3). Incidentally these gyroscopes were probably the largest that have ever been made, the rotors being 15 ft. in diameter and weighing 100 tons each. This installation—which was designed by the Sperry Gyroscope Company—was entirely internal, but another method of ship's stabilisation—the Denny Brown—works on different principles in that fins protrude from each side of the ship and these are gyroscopically controlled to work against an incipient roll, somewhat on the same lines as the ailerons of an aircraft (Fig. XX. 4). As the ship starts to roll to port, the fin on the port side moves downwards and that on the starboard side moves upwards—the actual movement deriving its power

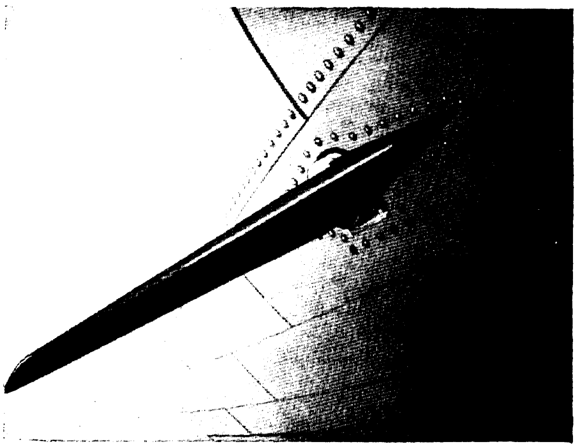


Fig. XX. 4. The Denny-Brown gyro controlled ship stabilising fin.

from hydro-electric apparatus, controlled by a small gyroscope that has a most ingenious anticipatory action, depending on a clever arrangement of springs which precesses the gyro, so causing the opening of the operating valve of the power unit *before* the ship begins its movement to one side or the other.

This system was actually installed in the cross-Channel steamer *Isle of Sark* in 1936 and was found to reduce the free rolling of the ship by sixteen degrees. Strangely enough, the reduction in rolling by this system was always sixteen degrees irrespective of the amount of free roll that the ship would develop were the gyro stabiliser not put into action. Thus, if the roll due to the waves was less than sixteen degrees, the stabiliser would eliminate it. If the free roll was thirty degrees, the stabiliser would reduce it to fourteen. An actual record of the effect is shown in Fig. XX. 5.

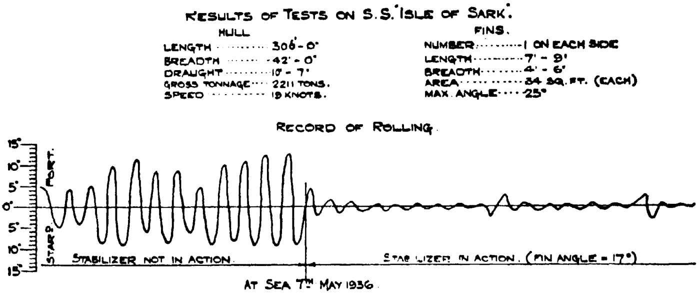


Fig. XX. 5. Rolling of the *Isle of Sark* without (left) and with (right) its gyro stabiliser in action.

The Gyro Pilot in Aircraft

Although in 1911 gyroscopic equipment was fitted to an aircraft to provide stabilisation, its mode of working was quite different from that in ships just described. It was indeed an anticipation of the ship's auto-pilot along which lines it has since developed. The present gyro-pilot for aircraft known throughout the R.A.F. as "George" operates not by directly balancing or counterbalancing the aircraft, but by operating the flying controls.

There are various systems, but the essentials of all are one or more gyroscopes, which control the aircraft laterally, i.e. in roll; longitudinally, i.e. in pitch and directionally, i.e. in yaw. In all cases the gyroscope governs a detector element or pick-off which may be pneumatic or electric, and this in turn operates pneumatic, electric or hydraulic servo mechanisms coupled to the flying controls. When the aeroplane is set on a given course, the gyro controls are inactive until some disturbing force tends to divert the aircraft from its course in any plane, when the appropriate control is brought into action to operate rudder, elevators or ailerons as required.

The rotors of aircraft gyroscopes have generally been air driven in contrast to those previously described, which are all electrically driven, but the method of driving the rotor is quite an incidental, and there are indications that aircraft gyro rotors will soon all be electrically driven.

As with ships, gyro control of aircraft means that a given course is followed more accurately than could be hoped for by a human pilot at the controls, small deviations that the human pilot could not detect being corrected before they have had time to develop, but the gyroscope will not, of course, correct for drift, and if the whole aircraft is carried to port or starboard by a cross wind, the gyroscope will not make any necessary correction to the course. What it will do is to keep the aircraft heading as it was originally set and in so doing—provided this is the correct course to be made good—it will save fuel and also pilots.

Of the instruments used on aircraft for navigational or piloting purposes those gyroscopically operated are the rate of turn indicator, the direction indicator and the artificial horizon. Additionally, aircraft bomb sights now incorporate gyroscopes as a vital component, and in both aircraft and ships gun platforms are gyroscopically stabilised so as

to provide a steady firing platform free from the disturbing movement of either ship or aircraft. Such applications are, however, unsuitable for brief summarised descriptions, and information on the instruments may be found in the book cited at the end of this chapter, though security reasons have precluded detailed reference to the other applications.

The Gyroscope in the Torpedo

One of the oldest and at the same time one of the most ingenious applications of the gyroscope is for the directional control of the torpedo. Here the gyroscope satisfies much the same function as in the auto-pilot for ships and for aircraft, but the control is directional only, i.e. the gyroscope ensures that the torpedo shall follow a predetermined course in azimuth, but it does not control the depth at which the torpedo travels. It operates on much the same principle as the ship or aircraft directional control in that the gyroscope controls the steering engine of the torpedo—which itself is air-driven—which operates the rudders, but there is one very important requirement to be satisfied by torpedo gyroscopes that does not apply in other applications.

It is essential that the gyroscope of the torpedo should not be spinning until the actual moment of discharge of the torpedo when this is set on its required course. It is equally essential that the gyroscope should be able to take directional control immediately. In other words it must be accelerated from rest to operating speed in the minimum of time, and as, owing to restriction of space the gyroscope must be small, its speed must be high. By a very ingenious spring, operating a ratchet that engages with the axle of the rotor, the rotor is accelerated from rest up to 9,000 r.p.m. within less than half a second of the discharge of the torpedo, and then a valve is opened from the torpedo compressed air supply by which the gyro is further accelerated up to its full operational speed (about 27,000 r.p.m.) at which it is kept spinning during the run of the torpedo by air jets directed into cups or buckets cut in the periphery of the rotor. In some designs the whole of the gyro drive is by air—the rotor is not started by spring action.

As soon as it strikes the water, the torpedo may deflect to either port or starboard, and when this happens the gyroscope opens a valve that sets the steering engine into action to give requisite correcting rudder. The rudder applied by the steering engine is full starboard or port, as the case may be, with the result that the torpedo is over-corrected and if starboard rudder has been applied the torpedo will swing off its course to starboard. Then the gyro, opening the opposite valve, will apply port rudder and so, for the whole travel of the torpedo, the rudder is being continually deflected from full port to full starboard and back again, with the result that the course of the torpedo is a series of sine curves. The depth at which the torpedo travels is determined not gyroscopically but by hydro-static valves that operate horizontal rudders (corresponding to the elevators of an aircraft) and the rudders operated by the gyroscope are, of course, vertical.

The maximum run of a torpedo averages approximately ten minutes, during which this lethal weapon may cover as much as seven miles, and at the end of its run when the air supply has finished, the torpedo in peace-time comes to the surface where it remains floating, but in war-

time when the war head with its charge of explosive is fitted, the torpedo sinks to the bottom so that it shall not be recovered by the enemy, who might learn some useful lessons from its detailed construction.

For further information on this subject the reader may refer to the Publisher's book "The Gyroscope and Its Applications," from which the illustrations in this chapter have been drawn.

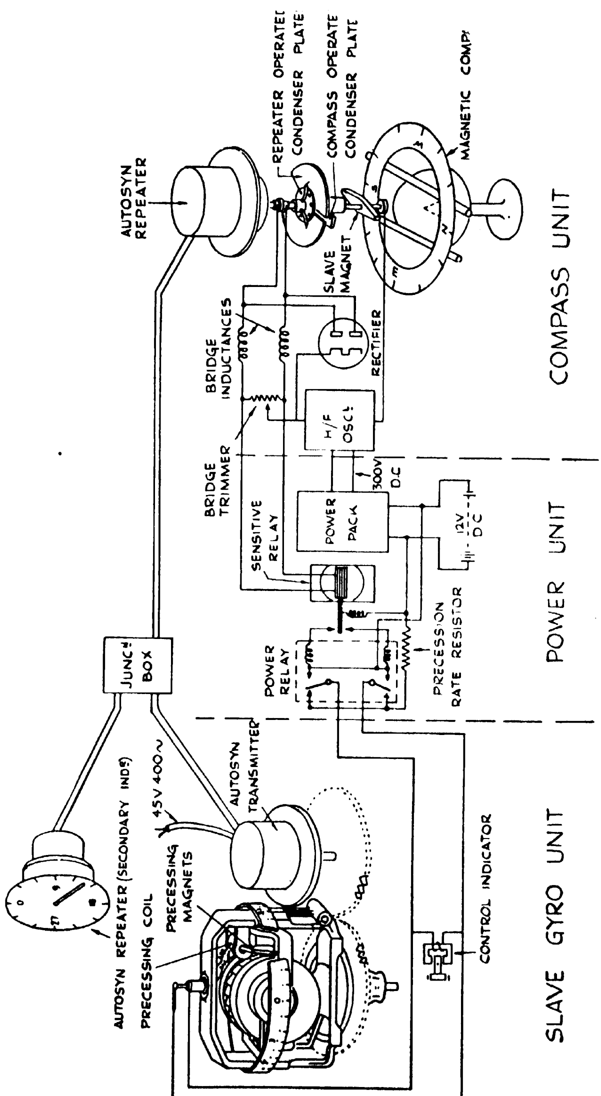


Fig. XX.6. An example of co-operation between the gyroscope and the magnetic compass—the Sperry slave gyro magnetic compass in which a magnetic compass is used to correct the free precession of a gyroscope and provide a direction indicator (not a gyro compass) in aircraft. The readings on the dials are magnetic compass courses transmitted through the gyroscope.

CHAPTER XXI

THE MARINER'S COMPASS

Everyone knows that the compass needle, which consists of a bar of magnetised steel freely suspended and balanced on a pivot, points to the magnetic north. No one knows why, and it is surprising how few people know that, with few exceptions in time and place, a compass needle does not point to the true North.

It used to be thought that the magnetised needle was attracted by a mass of lodestone (magnetic ore) situated somewhere in Labrador, but as the variations of the needle, i.e. the amount by which it points away from true North, change continuously, the idea of a fixed material attraction is obviously untenable. In May, 1945, an R.A.F. investigating Lancaster found the north magnetic pole some 300 miles from where it was supposed to be. All that we can say is that the earth constitutes a magnetic field which has the effect of making the compass point in a certain direction at a given time and place—this direction being *approximately north and south.*

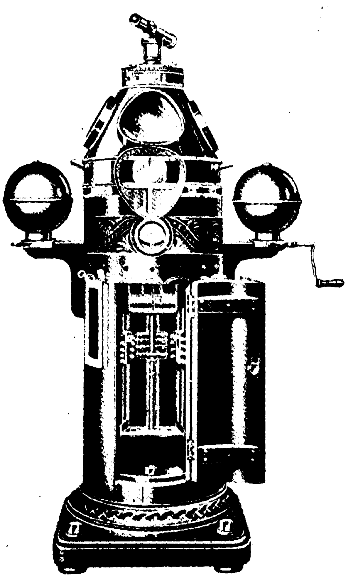


Fig. XXI.1. A rather old standard binnacle and compass with a telescope for taking bearings, a handle for adjusting the correcting spheres and the door open to show the corrector magnets in their adjustable housing.

When Columbus sailed for America (in 1492) his compass was pointing to the east of north and when he was well across the Atlantic discovery of changes in what is now known as magnetic variation was an important factor in frightening his crew into mutiny.

In 1657 the compass in London was pointing true north. It now (1945) in London points about 10 degrees west of north and, also in London, it will point true north again in about one hundred years' time. The maximum variation recorded (at London) was 24½ degrees west in 1816, and the period of a complete cycle from true north to maximum variation and back to true north is about three hundred and sixty years.

This magnetic variation, which changes continuously, is not the only wandering from true north to which the compass is subject. Each compass may have its own more or less permanent individual

error and in addition every compass has an error when installed in a ship (or aircraft) due to the magnetic attractions of various components of the ship. These errors are spoken of as deviation and are not constant. A steel ship when being built acquires its own magnetic field which affects every compass placed on board, and these errors have to be checked by "swinging" (see below). The same thing applies with aircraft, though here the matter is further complicated by the number of electrical services and the impossibility of installing a compass at an absolutely safe distance removed from them. The swinging of an aircraft or ship for compass correction should be done with all local electrical services working.

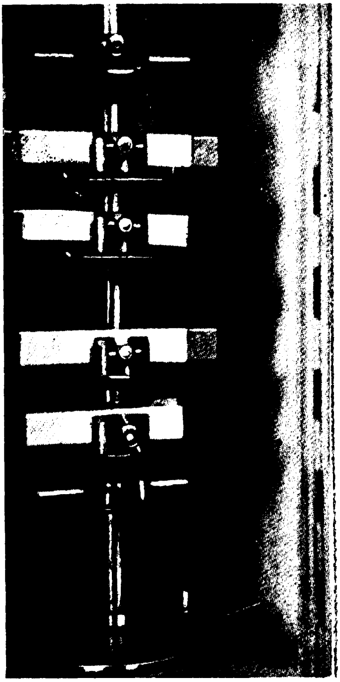


Fig. XXI. 2. Details of the arrangement of correcting magnets in the pedestal of a compass binnacle (*reproduced from Motor Boating*).

Every compass needle if freely pivoted at its centre of gravity will dip towards the magnetic north in the vertical plane just as it will rotate towards the magnetic north in azimuth. This dip, as it is called, varies at different places on the earth's surface just as does the variation, but is generally compensated for in the mounting of the compass needle or card in its bowl. Sometimes variation mentioned above is spoken of as declination, which is apt to cause confusion with dip but the two things are distinct.

Additionally there is what is known as local variation—this being due to local magnetic fields in some places on the earth's surface that affect the reading of the compass. For instance there is a mountain in Africa where the shifting of a compass through a distance of not more than 100 feet will affect its reading by no less than 10 degrees. If a compass be taken to somewhere on the line between the North Pole and the North magnetic Pole, the south pole of the compass needle will point to true north. Further, there is a daily variation in the reading at any given place though, fortunately, this is so small as to have no practical significance. Other variations either so small or so rare as to have little practical significance, although they may acquire this in special circumstances, are the daily or seasonal variations, for the reading of a given compass varies with the hour of the day and with the season, being at its greatest in spring and summer and less in autumn and winter, and

there is a variation due to such natural phenomena as magnetic storms. The amount of these spasmodic variations, any one of which cannot, of course, be previously estimated, is in any case so erratic that it cannot be allowed for generally.

There are instructional books giving elaborate information about the necessary correction for all possible calculable errors, and there are maps ranging from the county maps of England and Wales to maps of the world on which magnetic variation is indicated. This variation is shown on a map by lines drawn through places where the variation is of equal amount—the lines being known as isogonals, corresponding to the perhaps better known isotherms and isobars drawn through places of equal temperature or equal barometric pressure. Isogonals are apt to follow even more erratic curves than are isotherms.

At one time the line of no variation on a world map (on Mercator's projection) started at the top of the map at longitude 25° East, followed the line of longitude more or less straight to the Black Sea, then curved slightly eastward to the eastern tip of Africa, thence crossed India almost horizontally, and then proceeded south-easterly through Singapore, to leave the southern boundary of the map at a longitude of 150° East. The corresponding line of no variation in the Western Hemisphere started at the top of the map at longitude 105° West, passed through the magnetic North Pole and left the bottom of the map at longitude 30° West—the line being approximately straight. The eastern coast of Asia was covered by irregular ellipses—one of which was of no variation at all, and those inside it indicated variation of different amounts. The whole series of lines was at a casual glance utterly confusing but was, nevertheless, of great importance to the navigator.

With local maps, especially when one is taking accurate bearings as for surveying or artillery fire, the marking of the magnetic variation is of supreme importance, and on all maps worth the name the variation is given for a year (also named) with the amount of annual change, thus for example "1930, 15° West decreasing 10′ annually," which would mean that in 1945 on that map the annual variation would be $15° - 2\frac{1}{2}°$; in other words $12\frac{1}{2}°$—except that extrapolation over such a long period would be a very risky process.

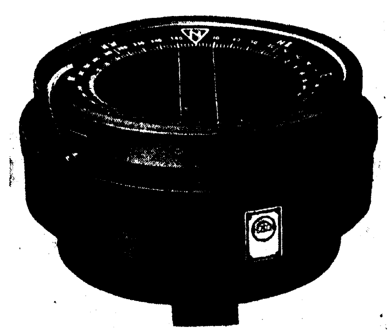


Fig. XXI.3. The P 4 aircraft grid steering aperiodic compass, luminised for reading at night.

History

Although, like many other things, the origin of the compass is frequently attributed to the Chinese (about 5,000 years ago), there may be little more solid basis for this legend than for many of the others. Almost all that we know definitely is that the first reference to the compass in European literature was made by Alexander Neckham in the 12th century,

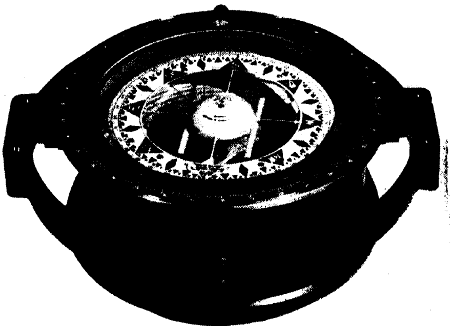


Fig. XXI. 4. Fleet type dead-beat compass with 10 in. bowl and 6½ in. card. The short magnets may be seen at each side of the central dome in the bow.

and that a century later Roger Bacon referred to it as an article in everyday use, which was a habit of the mediæval schoolman, much to the annoyance of modern investigators trying to probe into origins. In the same century, the 13th, the compass was definitely being used by the sailors of Amalfi on the west coast of Italy, but what kind of instrument it was and of what real value it was, are matters of conjecture. It is sometimes said that a piece of hollow iron, probably shaped like a fish, was rubbed with lodestone and then floated in a bowl of water, or a small bar of iron after being rubbed with the stone, was floated in a bowl by being fixed to some straw. When one thinks of the care that is taken and that is necessary to give even approximate accuracy for the modern compass one can only guess as to what sort of readings these primitive "instruments" gave, and it is little wonder that magnetic variation was not discovered until the compass had been in use for two or three centuries. Stories about the compass having been introduced by travellers from the East—such as Marco Polo—are of more than doubtful validity. It can, however, be said definitely that in Sir Henry Yule's standard edition of Marco Polo's travels there is no reference to the compass in the text.

The next stage in the development of the compass was the provision of a needle pivoted above the centre of a circular card that was divided into 32 points, and the card was turned so that the North on the card came under the North seeking end of the compass needle. In other words, the card was orientated by reference to the needle, and this type remained in use until the end of the 18th century, though a card fixed to the needle and pivoted as delicately as possible, so that the attraction of the needle to the North directly turned the card if this were displaced, had been introduced 300 or 400 years earlier. This type—the dry card compass—remains in use to this day on more or less rigid platforms such as in land surveying and on big ships. It may give greater sensitivity than the liquid type, which is now far commoner, but it takes longer to settle and is more liable to disturbance by extraneous influences.

To facilitate and speed up the settling of the card after a disturbance—and to limit disturbance—the next step taken was to fill the bowl in which the card was suspended with liquid, so that all movement of the card was damped by friction with the liquid. Disturbance of the compass was then reduced, and once the card had settled, disturbance was more difficult to initiate. These effects were further increased by the pro-

vision of damping wires mounted underneath the card giving what was sometimes referred to as the dead-beat compass, which was comparatively difficult to disturb. Although dead-beat compasses have very considerable assets and are used on small craft at sea and on aircraft, it is significant that the Admiralty prefer the absence of the dead-beat feature.

Types of Compasses

Compasses in regular use to-day range from the small pocket compass used by the soldier for determining his direction of march or for orientating his maps by which he may lay his guns, to the heavy instrument with a bowl up to about a foot in diameter, mounted in the binnacle on a ship's bridge. All of these compasses may be of the dry card or liquid type but in certain applications, e.g. aircraft, the dry card is never used, and in all a very vital consideration is the mounting of the needle on its pivot. Two contrary requirements impose themselves, the maximum possible freedom in movement is wanted but at the same time it is required to check the effect of disturbance and the tendency of the needle to point downwards to the pole which, in the neighbourhood of London, involves a vertical angle of 66°. If the needle is suspended at some point other than its centre of gravity so that it is horizontal at any given place it will not be horizontal if taken any appreciable distance away north or south, and various means are adopted to overcome this difficulty, such as mounting the needle between double pivots or weighting one end of it or, most commonly, making the magnetic element pendulous. Any method adopted has its disadvantages, but the supreme consideration at all times is freedom of horizontal movement. For this reason the needle generally has jewel mounting on a fine steel pivot or point fixed to the bottom of the bowl in which the whole assembly is encased.

It was thought at one time, somewhat naturally, that the larger the needle its directive force would be proportionately greater, and it was a long time before the fallacy of this was conclusively demonstrated. Use of a large needle introduced many complications, mainly in the way of increasing inertia, friction and magnetic deviations. The modern tendency is to go to the other extreme and use a short needle—if necessary increasing its directive force by using more than one in the same compass. It is rare to find a modern compass with a needle more than 4 inches long, but it is common to find a compass with several needles mounted parallel to each other with a maximum length of 3 inches and spaced according to definite rules such as that the diagonals of the rectangle meet at an angle of 60°. In small instruments such as those intended for the pocket, which often attain a very satisfactory degree of accuracy, the needle is, of course, considerably smaller. Constant development and improvement in the practice of mounting the card and the needle as a single unit, immersed in liquid, introduced complications by the inertia of the card and its friction in the liquid. Thus the next step was elimination of the card, and many compasses to-day, especially those used in aircraft, have no card at all. Instead, two parallel lines called grid wires are drawn on the glass cover of the bowl containing the liquid, the rim of the bowl is marked in degrees, and to set a course the lines on the glass are turned to point to the desired course in degrees and the pilot steers by keeping the compass needle parallel to the two lines.

Most compasses are read by direct vision on to the card or grid wires in the bowl, but in some cases a magnifying lens is interposed so as to make reading easier. In others, especially in hand compasses, a prism is used which, in conjunction with a sight, enables the observer to look at the object of which he wants a bearing and to read off the bearing through the prism, simultaneously.

Elaboration of the idea which involves many complications and is an elaboration in principle being entirely different in practice, is the distant reading compass which is now used extensively on both air and marine craft. In this system the compass itself is housed at the most convenient point in the body of the ship or aircraft, and its reading is transmitted electrically to dials where they can readily be seen by pilot and navigator. The advantage is, of course, that the compass can be housed in the most favourable and least vulnerable position; the disadvantage is that should the master compass be damaged, the distant reading dials are useless.

Calibration of Cards

Every compass bowl, with a very few exceptions, has on it what is known as the lubber line or lubber mark. This is a mark or line indicating the fore-and-aft line for installation of the compass wherever it has to go, generally so that it may be placed on the strict fore-and-aft line of an aircraft or ship and the lubber used as a datum mark or line. From this line on the bowl, the bowl or card, or both, are calibrated. In early compasses the card alone was calibrated in points and the ability to recite these points in correct order was and is known as "boxing the compass."

In recent years the use of points has been almost entirely supplanted by degrees and it is now only on small craft and trawlers that one hears of a course being given in points. For compasses on seagoing craft the card is divided into four quadrants each of 90° making 360° all told, but in aircraft compasses and in some that are used afloat the calibration is continuous from 0° to 360°.

Mounting of Compass Bowls

The deviation of a compass is corrected as far as possible by the provision of magnets underneath the bowl, and these magnets and other means of correction are usually incorporated in the compass bowl mounting. This mounting has as its primary functions the housing of the compass and its insulation from movement of the vehicle—a ship or aircraft (or Army tank). In the case of a ship, where movements are comparatively slow and regular, the compass bowl is supported by means of two pairs of trunnions at right angles to each other, each of which allows a swing in the vertical plane thus, at whatever angle the whole support may be tilted (within limits), the compass bowl can remain level. This mounting is, however, unsatisfactory on aircraft where movements are rapid and comparatively violent and where there is a large amount of vibration. There is a definite limit to the range of gimbals—as this trunnion mounting is called—and the limit may often be exceeded in an aircraft though not in a ship. In aircraft the compass

bowl is usually supported in an anti-vibration mounting consisting of springs with or without rubber or felt pads and without gimbals.

In any case, whether gimbals are provided or not, the mounting for the compass bowl has immediately underneath the bowl a compartment for the housing of small magnets which may be inserted as required to correct any particular deviation of a compass needle. As the correction due to any particular magnet is affected by any turn in azimuth of the whole mounting, the job is not by any means as simple as it might seem and resolves itself into a matter of compromise between reducing error at one point at the cost of increasing it at another.

In ships the bowl and its mounting are housed in a binnacle—a pillar of anything up to about 5 feet in height on each side of which is an iron ball adjustable for distance from the centre line of the binnacle. These balls also exert an attraction on the compass needle and are used in conjunction with the magnets in the corrector box for correcting deviation. In some of the more elaborate binnacles the magnets inside the binnacle are attached to a small brass chain running round pulleys at the top and bottom of the binnacle and so the magnets are readily adjustable for height and thus for their effect on the compass needle, so that adjustments may be effected by raising or lowering the magnets for correction of errors introduced by rolling of the ship.

In addition to housing the compass, the binnacle almost invariably has provision for lighting the compass bowl so that this may be read at night. The old-fashioned way was to have a light shining down on to the card; an alternative is to give the bowl a glass bottom and use a semi-transparent card which may be illuminated from a small electric bulb placed underneath the bowl.

It will be noted that the correction provided in the compass housing is all for deviation of the compass and not for variation, which must be allowed for according to the time and place at which readings are taken. There are, however, other compass errors that cannot be compensated for mechanically or even by calculation—thus there is the northerly turning error in aircraft as a result of which when an aircraft turns from east to west or vice versa through north, the compass needle may swing until the north-seeking pole is pointing due south and the aircraft must fly for several minutes on a straight and level course before the compass will settle correctly after this violent wandering.

If the bowl of a liquid compass is not absolutely full of liquid, and in extreme circumstances even when it is, the liquid in the bowl may develop a swirl and start rotating, dragging the card round with it. A liquid compass on a small yacht crossing the Channel in a swell with the ship rolling moderately, has been known to swing more than once through a complete circle, and while these gyrations are taking place, the compass is, of course, quite useless as a direction indicator. All liquid compasses are provided with means for replenishing the liquid or eliminating the bubble whenever an air bubble appears, but the work needs to be very carefully done and is not a job for an unskilled operator. The liquid normally used is a mixture of water and alcohol or glycerine, or both. To reduce the effect of liquid swirl, sometimes the bowl is made much larger than is necessary to accommodate a card of a given size for the swirl originates at the sides of the bowl and if the margin

between bowl and card be large enough, the swirl may never seriously affect the card itself.

Other Types of Compasses

In the past quarter of a century a compass has been introduced that does not depend upon the attraction of the earth's field or a magnetic needle. This is the gyroscopic compass, which depends on the principle that a freely-mounted gyroscope immune from any friction will maintain a fixed direction in space, i.e. will remain constantly pointing to any given fixed star, though this in itself does not constitute a compass. Further information on this type of compass is given in Chapter XX on Gyroscopic Instruments.

Another and comparatively new type of compass is the fluxgate, which consists, briefly, of several symmetrical solenoids arranged usually as an equilateral triangle through which alternating current is passed that is affected by the earth's magnetic field so that the varying current through the solenoids may be made to give a reading on a dial which can be translated into the points or degrees of a compass card. The fluxgate compass is maintained in the same horizontal plane by means of a gyroscope and its readings are taken on distant dials at convenient places in the ship or aircraft. This type of compass is, of course, subject to magnetic variation and deviation but not to dip nor to the mechanical difficulties of pivoting the needle, though it has many mechanical complications of its own.

While these two compasses have advantages over the magnetic compass, it is unlikely that they will ever supersede it completely because they depend on the provision of an electricity supply and if this should fail for any reason, a ship or aircraft would be without any direction indicator. Although most big ships to-day have and rely on their gyroscopic compasses, there are magnetic compasses as stand-bys on board.

In conclusion, there is one point about the use in this chapter of the term "north pole of a compass needle." More correctly this should be spoken of as the north-seeking pole. It is well known that magnetic poles of the same polarity repel each other and attraction exists between poles of opposite polarity. The end of the compass needle that points north is thus, in one sense, the south pole of the needle, but it is an established convention to refer to it as the north pole as a convenient abbreviation for the north-seeking pole, and in practice this north-seeking end of the needle is referred to as the red pole—being painted this colour—while the opposite end is the blue pole.

CHAPTER XXII

THE SEXTANT

A sextant is an instrument used to measure the angle subtended by two objects at the place of observation, a feature of the instrument being the simultaneous sighting of the two objects by the eye of the observer. It is most commonly used for navigational purposes for the measurement of the altitude of the sun or a star above the horizon, but it is also used to measure the angular distance between any two objects not necessarily in the vertical plane.

Early Instruments

The measurement of angles, and particularly of the altitude of the sun and its seasonal variations, has been practised for thousands of years,

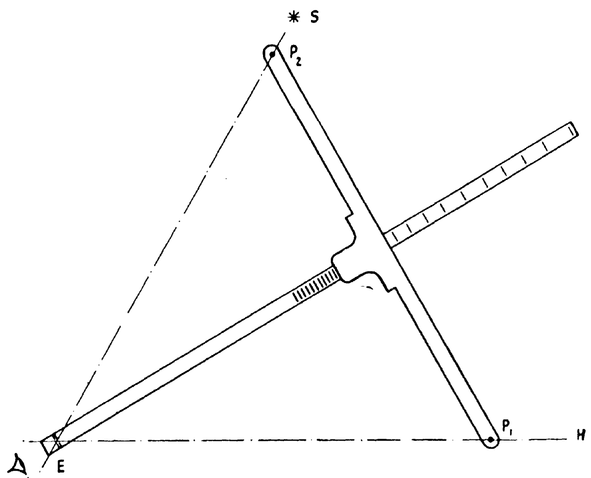


Fig. XXII. 1. **The Cross Staff** used by mediaeval navigators. The eye at E observes the horizon at H past pin P_1 and the heavenly body past the pin P_2.

although the application of such observations to navigation is of comparatively recent date. Ulysses would have reached his home in Ithaca in considerably less than ten years if he had been able to navigate out of sight of recognisable land. In the fourteenth century the only instrument available for the navigator was the cross-staff shown in Fig. XXII. 1, which can be considered to be the forerunner of the sextant. The cross-staff consisted of a lath about 3 feet long graduated in angles and provided with a peep-hole sight. Sliding on this lath was a cross-member about 26 inches in length, maintained at right angles to the lath, and having at its ends two fore-sights which were aligned with the two

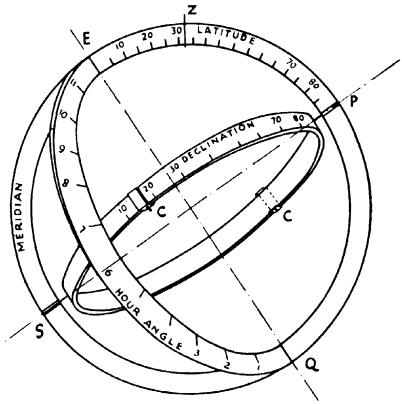


Fig. XXII. 2. **Astronomical rings.** EZPQS represents the meridian, Z is the zenith, EZ the latitude, P and S the north and south poles. The equatorial ring EQ is divided in hours and also in months and weeks. The declination ring is divided in degrees, months, the zodiac, etc. CC are sights movable on the declination ring.

objects simultaneously by sliding the cross-member to and fro while keeping the eye at the peep-hole.

About the same time, or a little later, the astrolabe was introduced. This consisted of a heavy metal circular disc hanging from a ring and provided with a pair of sights on a bar or alidade which pivoted about the centre of the disc. The altitude of the sun was observed by means of these sights while the disc was held suspended so that it hung vertically. In 1534 Gemma Frisius introduced the astronomical rings shown in Fig. XXII. 2. This instrument was much more elaborate than the astrolabe and could be used for a number of purposes based on the measurement of the altitude of the sun. It was graduated in latitude along the outer main ring, in hours and in months and weeks on the equatorial ring, and the inner moving declination ring was graduated in degrees, months and weeks, the signs of the Zodiac, and with a tangent scale for the measurement of heights.

The vernier was invented by Pierre Vernier, of Brussels, in 1631 and the increased accuracy thus obtained stimulated the invention of more accurate methods of observation. Towards the end of the 17th century Newton and a number of others suggested the use of a mirror to reflect the light of the sun into the sight, and in 1733 John Hadley in England and Thomas Godfray in Philadelphia simultaneously produced the sextant in very much the same form as it is used to this day.

The Marine Sextant

It is well known that if a beam of light is reflected by a mirror any rotation of the mirror through a given angle in the plane of incidence will cause the reflected beam to be rotated through double the angle. Figs. XXII. 3 and XXII. 4, show how this principle is applied to the sextant and how it is possible to see both objects in the same direction simultaneously; a very great advantage when the instrument is held in the hand and used on a moving platform such as the deck of a ship. It will be seen from Fig. XXII. 3, that if the two mirrors M_1 and M_2 are placed parallel to each other a distant object will be seen by the eye by direct light past the edge of M_1 and by two reflections in M_2 and M_1. If now M_2 is rotated about an axis perpendicular to the plane of the

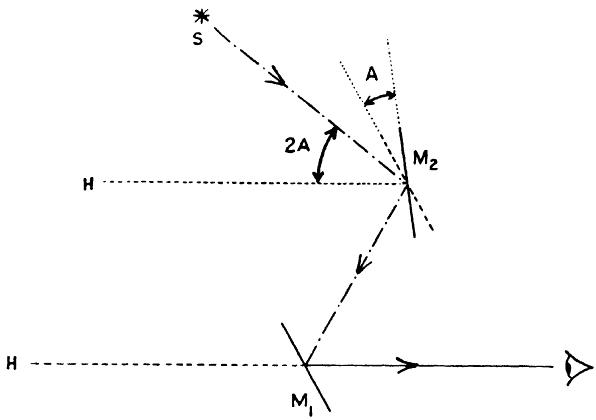


Fig. XXII. 3. **Principle of the sextant.** The horizon H is viewed through the clear portion of the horizon mirror M. The star S (or sun) is viewed by reflection in the index mirror M_2 and in the silvered portion of M_1 and is made to coincide with the horizon.

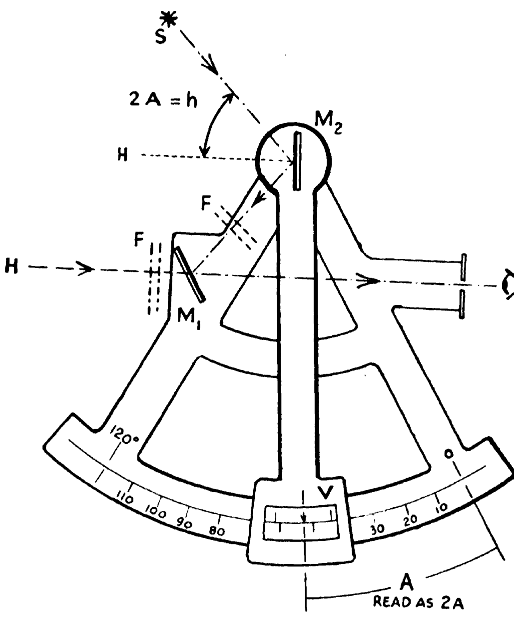


Fig. XXII. 4. **Diagram of a modern sextant.** The altitude of the star or sun, S, is read directly on the scale at the vernier V. M_1 is the horizon mirror, M_2 the index mirror. F are sun shades of neutral filter glass.

diagram so that a second distant object, such as S, is seen by reflection in the two mirrors, then by adjusting M_2, this object can be brought into coincidence with the first distant object seen directly past the edge of M_1, and the angle between the two objects is clearly equal to double the angle through which M_2 has been rotated.

In the actual sextant shown in Fig. XXII. 4, the horizon mirror M_1 is made of good parallel glass and is silvered over only one half of its surface, usually

the half nearest the framework. It is also provided with adjusting screws so that its plane can be made truly perpendicular to the framework. The index mirror M_2 is fixed to the index arm which is itself pivoted on the framework. The index mirror is fully silvered and in some instruments is made adjustable so that its plane can be made perpendicular to the instrument, but this adjustment is usually considered to be the responsibility of the maker. For observation the instrument is provided with one or two telescopes and a dummy tube with a peep-hole, and the telescope bracket is also capable of adjustment so that the optical axis may be made parallel to the instrument and at such a height that the reflected light and the direct light can be made equal in intensity. A series of neutral or coloured filters is fitted to the sextant as shown by the dotted lines in Fig. XXII. 4, so that they can be interposed between a bright object and the eye to cut down glare and to enable an observation to be made in comfort and safety. The framework itself is light but rigid in construction and may be of brass, bell-metal, bronze or a light alloy, and it is shaped like the sector of a circle. Along the arc of the sector is a scale graduated so that each 30-minute interval is marked as one degree. The index arm moves across this scale as it is rotated and it is always provided with a clamp and a fine adjustment screw. The angle may be read by a vernier or, in more modern instruments, the edge of the sector is cut in the form of a worm wheel and fine adjustment is obtained by turning a screw provided with a micrometer head which is divided in minutes.

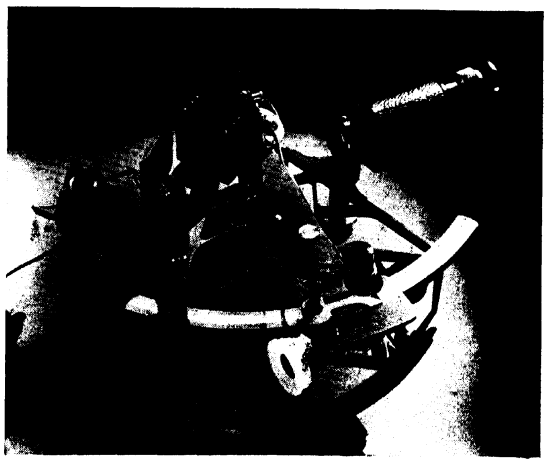


Fig. XXII. 5. **A modern micrometer sextant** with an artificial or bubble horizon, the principle of which is illustrated in Fig. XXII.6.

Fig. XXII. 5, is a photograph of an actual marine sextant on which the mirrors and shades can be seen. This particular instrument is shown fitted with a prismatic telescope and with a detachable bubble

artificial horizon in addition to the horizon mirror. This bubble can be used if the true horizon is not visible and a similar construction is much used in air sextants (q.v.).

Method of Use

For the measurement of altitudes the instrument is held in the hand and the sun or star observed by reflection in the two mirrors is brought down on to the horizon as seen past the edge of the horizon mirror. The angle is then read and the time of the observation noted. If the peep-hole sight is used the field of view is seen divided vertically by a line on one side of which the sun or star is seen and on the other side the horizon. If the telescope is used the line is no longer visible and the two views are superimposed. If the horizon is not visible or if for any other reason it is not to be used, an artificial horizon can be used. The usual form of artificial horizon consists of a shallow trough of mercury protected from the wind by two sloping windows of optically flat glass. The mercury surface is, of course, horizontal but because of many difficulties attendant on its use, another form of artificial horizon consists of a copper plate amalgamated with mercury or even a plane mirror which can be levelled by means of a spirit level. In another form the bubble itself is used to indicate the horizontal direction as in the bubble attachment or air sextant. The use of a bubble for this purpose is by no means new, for it was suggested by Hadley in 1733 in the Philosophic Transactions for that year.

Errors and Adjustments of the Marine Sextant

Any instrument used for measurement is subject to errors of one kind or another and in any instrument consisting of moving parts adjustments are necessary and are invariably provided if the maximum value is to be obtained from it. The fundamental errors in the marine sextant are as follows:

(i) Eccentricity of the scale with reference to the pivot of the index arm. This error cannot be eliminated and therefore great care is taken in manufacture and the instrument is then tested at the National Physical Laboratory and a certificate is issued with it which states the amount of the error at all parts of the scale.

(ii) Lack of perpendicularity of the index mirror to the plane of the instrument. This is a maker's adjustment and no further alteration should be required but the instrument should be tested from time to time to ensure that the adjustment has been maintained. The simplest test is to look into the index mirror so as to see the reflection of the arc of the sextant and at the same time the actual arc; these should appear continuous. If an apparent break occurs where the reflected image joins the direct view the mirror is out of adjustment.

(iii) Lack of perpendicularity of the horizon mirror to the plane of the instrument and of parallelism to the index mirror in the zero position. This is a user's adjustment and screws are provided for the purpose. The instrument is adjusted by setting the index arm to zero and observing a star or small distant fixed object. Two images will be seen if the mirror is out of adjustment and these will pass each other as the index arm is moved. The screws are then adjusted until the images coalesce.

(iv) Lack of parallelism of the optical axis of the telescope to the plane of the instrument. The telescope can be raised or lowered bodily to equalise the light from the clear and reflecting parts of the horizon mirror and it can also be tilted slightly. The simplest test is to place the sextant on a table with two small sights of equal height fixed to the frame as far apart as possible and to orient the instrument so as to align these sights with a distant object. On looking through the telescope the distant object should then appear accurately in the centre of the field of view.

(v) Index error. This error is observed and allowed for every time the instrument is used to make an observation, and it is simply the error in the zero reading of the index arm when a single distant object is observed. If the instrument is in good order and adjustment, the index error will be small, but it may change slightly when the sextant is in use owing to expansion or small distortions and vibration.

In addition to the above five errors, sextants may suffer from lack of parallelism of the horizon glass or the index glass, and only extreme care in manufacture and possible newer designs will tend to eliminate these. Lack of parallelism of the index glass may become apparent as a double image if a very bright star is observed, but in any case this error is included in the eccentricity error tabulated by the N.P.L. Lack of parallelism of the horizon glass introduces a constant difference in the readings apparent as an index error. It has been suggested that for greater accuracy the index mirror may be replaced by a right-angled prism, and some sextants are now being made with this prism.

Bubble sextants similar to the air sextant are being suggested for marine work, and bubble attachments are also available for normal marine sextants. Although these bubble horizons can be extremely useful under some conditions of visibility, they must be used with care. If the ship is rolling or pitching in any way, the apparent direction of gravity can be considerably different from the true vertical, and large errors in reading will then result. The period of the pitch or roll on a ship is usually so long that it is not even possible to take the average of a number of readings with any certainty of success. On a steady ship, however, and in the air, where the period of random accelerations is small, the bubble sextant can be used.

The Air Sextant

Fig. XXII. 6, shows diagrammatically a form of sextant used for air navigation. In order to keep the instrument small, the sector shape has been abandoned and the index arm carrying the index mirror is now actuated by a cam in the shape of a spiral scroll on which a roller fixed to the end of the index arm bears. The bubble contains only the vapour of the liquid in the chamber and it can be varied in size or collapsed completely by altering the pressure on the fluid by means of a screw which presses against a corrugated diaphragm in the bubble trap. The bubble chamber is circular and its radius of curvature is carefully chosen so that for small angles of inclination the apparent vertical is always indicated on looking through the instrument. It is thus not necessary to keep the bubble always in the centre of the chamber when making an observation, and it becomes relatively easy to make a

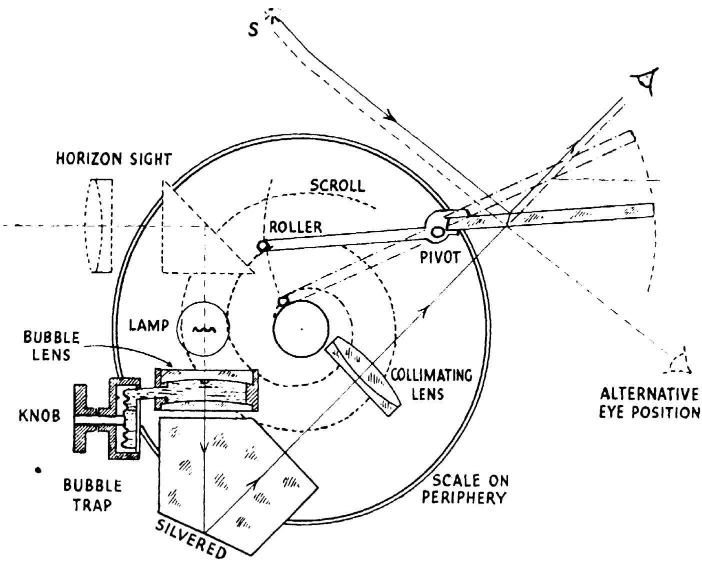


Fig. XXII. 6. **Diagram of bubble sextant.** The eye may see the star S by reflection and the bubble directly, or alternatively, the bubble may be seen by reflection and the star directly. The size of the bubble is adjusted by means of the knob on the trap. The lamp may be withdrawn and a visible horizon viewed by means of the horizon sight. The index mirror is tilted by means of the scroll which lifts the roller. The scroll is attached to the peripheral scale.

coincidence of a star with the bubble under the conditions peculiar to use in aircraft. The bubble is illuminated by a lamp the battery for which is fitted within the handle of the instrument. The light from the bubble is rendered parallel by a collimating lens and in use the bubble appears as a bright ring with a dark centre in a dark field. For use by day the diffused lighting makes the bubble appear as a small dark dot with a bright centre in a bright field. By fitting a prism and an auxiliary lens it is possible to use the instrument normally with a real horizon.

In later forms of air sextants the line of sight is made horizontal instead of inclined as in the diagram. In some forms the index mirror is mounted on a plate carrying pins which engage slots in the body of the instrument so that the mirror is pre-set to the expected altitude within 10 degrees and a fine adjustment is provided within this range for the actual observation.

These instruments are also fitted with averaging devices which either add together one-sixth of each of six independent readings or, by means of a clockwork device indicate the average continuous reading over a predetermined time. Thus it is only necessary to obtain a coincidence, set the mechanism in operation, and maintain coincidence until a shutter automatically cuts off the images. The reading is then taken and indicates the *mean* altitude of the star during the period of observation.

CHAPTER XXIII

SOUNDING EQUIPMENT

Mystery to a Phoenician seaman was a great principle of his profession, a principle he was obliged to support even at the risk of his own existence, for according to Strabo, when the captain of a Phoenician vessel who was on a voyage to the Cassiterides for tin, imagined that he was observed by a Roman, he immediately ran on a shoal and was shipwrecked, rather than forfeit the mystery of his voyage by giving the smallest degree of information to another country.

They carried their navigation under their hat, but although we have no record of the method by which the early navigators found their way about the sea, it is quite certain that from earliest times 2,000 years ago, the Greeks, the Arabs and the Phoenicians, all knew the approximate depths of the shallow waters they frequented.

Sea sounding began with the lead, and according to the Marine Dictionary in 1780 :—

"There are two plummets used for sounding in navigation, one of which is called the hand lead, weighing about 8 or 9 lb., and the other the deep-sea lead, which weighs from 25-30 lb.

"The former is used in shallow water and the latter at a great distance from the shore, particularly on approaching the land after a sea voyage ; accordingly the lines employed are called the deep-sea lead and the hand lead line. The hand lead line is usually 20 fathoms in length and is marked every 2 or 3 fathoms so that the depths of the water may be ascertained either in the day or night. At the depth of 2 or 3 fathoms there are marks of black leather ; at 5 fathoms there is a white rag, at 7 a red rag, at 10 black leather, at 13 black leather, at 15 a white rag, at 17 a red rag, ditto, ditto.

"The deep-sea lead is marked with two knots at 20 fathoms, 3 at 30, 4 at 40 and so on to the end. It is also marked with a single knot in the middle of each interval as at 25, 35, 45 fathoms, etc. To use this lead more effectually at sea or in deep water on the sea coast, it is usual previously to bring the ship to, the lead is then thrown as far as possible from the ship in the line of her drift so that as it sinks the ship drives more perpendicularly over it. The pilot feeling the lead strike the bottom, readily discovers the depth of the water by the mark on the line nearest the surface. The bottom of the lead being also well rubbed over with tallow, retains the distinguishing marks of the bottom, as shells, ooze, gravel, etc., which naturally adhere to it."

This primitive but sure method of sounding persisted until in 1850 more accurate measurement of deeper water was required, due to the introduction of steamships and laying of deep water cables. Many devices were tried such as that described as a Patent Sounding Apparatus which records upon a dial the depth attained.

Early Mechanical Sounding

To the lead was attached, upon the principle of the screw propeller, a small piece of clockwork, for registering the number of revolutions

made by the little screw during the descent; and it having been ascertained by experiment in shoal water that the apparatus in descending would cause the propeller to make one revolution for every fathom of perpendicular descent, hands provided with power of self-registration were attached to a dial and the instrument was complete. It worked beautifully in moderate depths, but failed in blue water from the difficulty of hauling it up if the line used were small, and from the difficulty of getting it down if the line used were large enough to give the strength required for hauling it up.

In 1872, Sir William Thomson, who was greatly interested in cable laying and designed most of his inventions in practice at sea, suggested the use of piano wire for sounding with a special form of winch. The idea was taken up in all countries, and from that time accurate and quick observations of depth at sea have been obtained.

Sir William Thomson also invented the Sounding Tube for use in balloon water or navigational soundings up to 100 fathoms, which consists of a glass tube open at the lower end. The water is forced a varying height up into this tube, according to the pressure which depends upon the depth of water reached at its lowest point. Either a chemical solution is used for coating on the inside which is then discoloured as far up as the water reaches, or a ground glass tube is used, which also shows a line of demarcation where the water level reaches its highest point. A scale is provided which is calibrated to read directly in fathoms of depth.

After the First World War, about 1923, stimulated by the use of powerful electric oscillators in sea water for sound ranging and submarine signalling, the propagation of sound waves in sea water was being experimented with in America, England, France and Germany. Suitable means of setting up sound waves capable of transmission through long distances, and receivers capable of detecting faint sounds reaching them, were among the results of this investigation.

Echo Sounding

Sir Isaac Newton first shows that the velocity of transmission of sound through any given medium is given by the equation:

$$V = \sqrt{\frac{\text{elasticity of medium}}{\text{density of medium}}}$$

In water, sound waves have a speed of propagation of nearly 1,400 metres (4,855 feet) per second, that is nearly five times faster than in air, in which the velocity of sound is about 330 metres (1,082 feet) per second. The velocity of sound in sea water has been determined with great accuracy in all parts of the world, and consequently, if the time taken for a sound wave to travel from the bottom of a ship to the sea bed can be accurately measured, then that would be a means of detecting the depth of water under the ship.

In practice it was not so easy as it seemed as the right sort of sound had to be produced and the means for picking up the return wave or echo, but from the early types of machine or device invented by Fessenden, Behm and Langevin, has developed an entirely new method of depth finding at sea known as Echo Sounding.

The principles employed in echo sounding have become established. A sound is transmitted from the hull of the ship; this sound wave travels to the bottom of the sea and is reflected back again as an echo. The echo is picked up by a receiver attached to the hull of the ship, and the time taken for the sound to travel from the ship to the bottom and back again, is a measure of the depth of water.

Echo sounding equipment is designed to produce the sound, receive and amplify the echo, measure the intervening time interval, and convert this interval automatically into units of depth measurement such as feet, fathoms or metres.

At the beginning of echo sounding a number of sonic or low-frequency transmitters were used such as electric hammers, oscillators, and even exploding a cartridge at the surface, but all these had a disadvantage in the measuring of small depths under the bottom of the ship so essential to safe navigation.

In shallow water the time interval is extremely short; for example, the time taken for a sound impulse to travel to a depth of 10 fathoms be reflected, and return to the ship, is about 1/40th of a second, and in the early days of echo sounding with sonic gear it was considered a great achievement to be able to take soundings down to 10 fathoms. The captain of the ship had a man in the chains at 10 fathoms and all soundings below 10 fathoms were taken from the lead.

An immense amount of technique was applied in sonic echo sounding to the separation of transmitter and hydrophone on the hull of the ship, to suppression of noise interference, and to slope correction, all which to a large extent were done away with by the introduction of the Supersonic Oscillator.

The Supersonic Oscillator

Pierre and Jacques Curres discovered that if the quartz is compressed it polarises electrically and produces a change of potential, and conversely if a potential is applied to the quartz it contracts and expands spontaneously. This is known as the Piezo electric effect, and Professor Longevin made use of this for both vertical and horizontal sounding. The transmitting and receiving unit of the Longevin type consists of a mosaic assembly of quartz crystals which are clamped between two metal plates, the thickness and the quantity of the plates determine the frequency at which the system will be resonant. One of the plates is in contact with the sea water and the energy is derived from the electric field between the two plates. The electric energy to excite the Peizo electric oscillator may be from an alternating current generator, but ordinarily excitation is produced by the high frequency oscillations resulting from the discharge of a condenser into an electric circuit.

This was the first supersonic echo sounder and had great success, the depths being shown either by a flashing light on a scale or recorded on smoked paper. By either system great accuracy was obtained. The Piezzo quartz transmitter at sea has been responsible for some of the most remarkable applications of sound waves, such as fish finding in shoals and the detection of submarines, but it is also very sensitive, and in the war it has had to be protected, otherwise it would be destroyed by mines or depth charges exploding in its vicinity.

Magnetostriction

The properties of certain metals to change their linear dimension when placed in a magnetic field has been applied to echo sounding, and is known as magnetostriction. When the magnetostrictive metal is in the field of a coil, should the coil be energised by an alternating electric current, the metal will alternatively contract and expand along the axis of the coil, in unison with the exciting current. Conversely, a fluctuating pressure applied to a face of magnetic material parallel to the magnetic field of the coil will cause changes in the field to produce an electromotive force across the terminals of the coil. Commercially pure nickel because of its high magnetostrictive property, its uniformity and its chemical and mechanical stability, is most frequently used.

The transmitter and receiver of a magnetostriction echo sounder consists of a pack of nickel stampings of the correct thickness and size, to obtain resonances, and wound toroidally so that an oscillating discharge from a condenser passing through the windings creates an oscillatory magnetic field in the stamping and this causes the mean diameter of the stampings to vibrate radially and conversely when the sound energy sets the receiver into vibration ; the magnetisation of the nickel stampings is altered periodically, and this sets up an oscillatory electric current in the windings.

The transmitter and receiver are housed in tanks filled with water, and the vibrations are transmitted by a conical reflector through the hull of the ship into the sea or vice versa. These oscillators are very strong and can stand considerable shocks. They can even be fitted in suitable form in direct contact with the sea water.

The depth of water is indicated on a flashing light scale or mostly on a recorder which can be described as the most important feature of echo sounding.

The Recorder

The Echo Sounding Recorder is a device which sends out a short pulse of sound from the bottom of the ship, measures the time required for the resulting echo to return from the bottom of the sea, and presents that measurement in the form of a depth measurement.

Fig. XXIII. 1, shows the schematic arrangement of a typical installation.

The motor drives through the gear train, the switch cam, to which is rigidly attached the stylus arm. As the stylus arm revolves the point is made to pass over the surface of the recording paper.

Once each revolution the switch-cam, by operating the transmitting contacts, causes a pulse of sound to be sent out from the transmitter in the bottom of the ship. At approximately the same instant the stylus passes the zero of the scale, as will be explained in detail later, the stylus marks the paper to show the interval between transmission and the echo line being received. This being directly proportional to the depth, the scale may be graduated in fathoms or any other depth unit.

The recording paper is chemically treated so that a current passing through the paper from a point such as the stylus, to a plate such as the tank front, will cause a brown mark on it. Hence, if a steady current

is passed through the paper from the stylus as it moves across it, a brown mark will record the track of the stylus point, but if a short pulse of current is passed through the paper at a definite position of the passage of the stylus, the mark will only appear at that position.

It is readily seen that such an arrangement may be used as a depth recorder by causing the return echo to supply a short impulse of current to the moving stylus at the moment of its arrival. As the ship goes into deeper water the stylus moves further across the paper before the echo is received, and the recorded line moves a corresponding distance across the paper. If the paper is made to move a short distance at a right angle to the movement of the stylus, for each passage of the stylus the successive echoes will form a contour of the seabed.

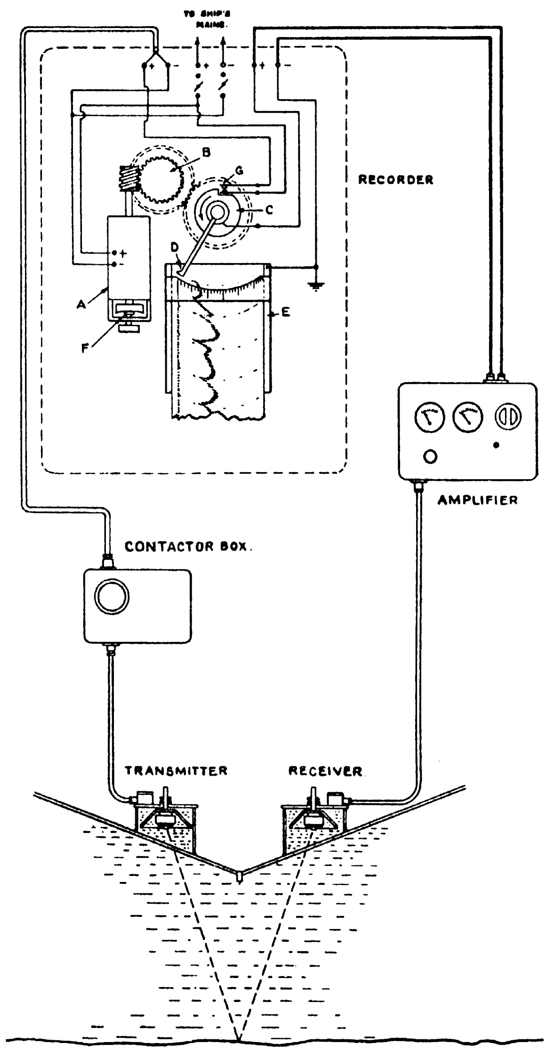


Fig. XXIII. 1. Diagram of the installation of echo-sounding equipment in a ship. Transmitter on the left and the receiver on the right.

A. Motor.	D. Stylus Arm.
B. Gear train.	E. Front of the tank.
C. Switch cam.	F. Automatic governor.

G. Transmitting contact.

The considerations governing the calibration of the scale are simple. The velocity of sound in sea water may be taken as 800 fathoms per second, so that it requires one second to go and return in a depth of 400 fathoms. Hence, if we divide a scale into 400 divisions and make the stylus move through these 400 divisions in one second, then for every fathom of depth the stylus will move through one division. If the switch-cam is adjusted so that the transmission occurs at the instant the stylus passes the zero division, then an echo from a 100 fathom depth will return as the stylus passes the 100th division, and the record will be made on the paper at the 100th division. Such a scale may be marked directly in fathoms. It is clear that recorders possessing different scales may be produced by simply varying the rate of travel of the stylus. It is also clear that, for any given recorder it is essential to keep the speed constant at the rated value. An automatic governor is fitted so that the speed varies very little with ordinary variations in voltage.

In the old days the words "On Sounding" in the log book was a source of satisfaction to the ship's officer, especially after a long voyage across deep water. In these days, although it has not yet been possible in merchant ships to sound all the way across the Atlantic, many remarkable feats have been achieved with the echo sounder recorder.

At 18 knots good records have been obtained in over 1,000 fathoms, but naturally the most valuable use is when approaching the 100 fathom line. In a fast ship like the *Queen Mary* it was of great value pre-war to approach the English Channel with continuous record from 250 fathoms right down to the 100 fathom line at full speed. This enables the navigator to plot on his chart a line of opposition and to dot the exact moment he crosses the 100 fathom line.

In coastal waters the echo sounder record gives such minute details of the bottom that a profile can be checked in the chart room to indicate the exact position of the ship even in dense weather.

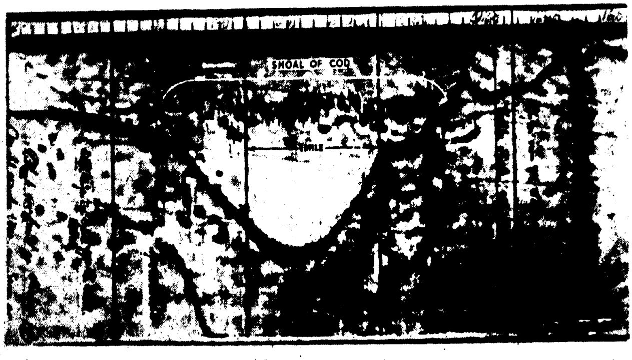


Fig. XXIII. 2. An example of what can be done by echo-sounding; a shoal of cod shown over a valley at the bottom of the sea.

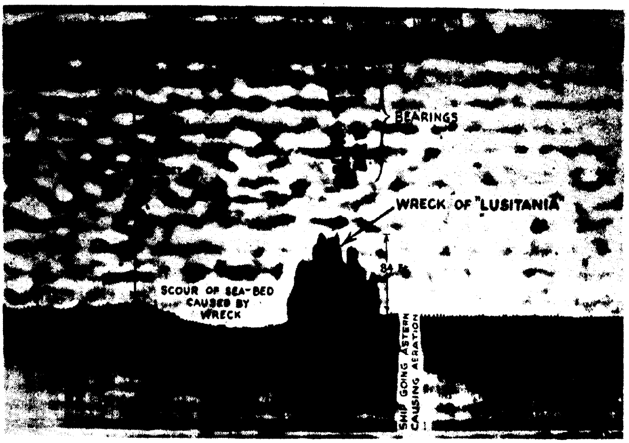


Fig. XXIII. 3. The wreck of the *Lusitania* revealed by echo-sounding in 309 feet of water.

In many parts of the world to-day ships literally feel their way over the bottom by echo sounder recording.

The echo sounder has many other uses, in trawling it is universal and large shoals of fish can be detected off the bottom. Seaweed can be found in places where it is prolific, and for wreck finding it is very reliable. The *Lusitania* was very quickly detected in the Irish Sea and profile runs made fore and aft and athwartship showed every detail (see Figs. XXIII. 2 and 3).

For survey work it is invaluable and gives an enormous amount of accurate detail in very quick time. The harbour and 35 ft. channel in most ports are regularly dredged by accurate measurement obtained from echo sounding down to 1 inch.

In the war submarine detection and convoy leading have been amongst its achievements ; many a mine has been found and the coast survey of Northern France at night with echo sounder parties in small boats led to the great success of "D Day."

CHAPTER XXIV

SURVEYING INSTRUMENTS

For the preparation of maps and plans, a topographical survey is made. To start with a reference line or base line is laid out and from this a network of survey lines is built up from which the topographical details can be located. The lengths of these lines and their bearings relative to the base line are measured and from this information the survey can be plotted in the drawing office. Also it is often necessary to know the height above sea-level of points in the area surveyed and to plot contours showing the slope of the ground. This information is obtained by levelling instruments which determine the height of a given point above some known reference level. Surveying thus calls for instruments which will measure lengths, angles and changes in level to a considerable degree of accuracy, and, since survey work is often carried out under difficult conditions, reliability and durability are also essential.

Measurement of Length

The Chain is the most commonly used instrument for measuring length on the ground. It is sufficiently accurate for the main lines of ordinary surveys, though for large surveys where extreme accuracy is required, a steel band, of the type described below, is necessary. The chain consists of 100 links of strong steel or iron wire. The end links are short and have brass handles attached to complete the length. Every tenth link is marked by a brass tablet, which has one point for the first ten links from the end, two for the second, three for the third, four for the fourth and the centre is marked with a circular tablet. Each tenth link is marked in the same way from the other end so that the chain can be used either way.

Two different lengths of chain are used, Gunter's chain which is 66 feet long from outside to outside of the handles, and the Engineer's chain which measures 100 feet. For measuring areas Gunter's chain has the advantage that 10 square chains equals one acre. Both chains have 100 links. For convenience in carrying the chain is folded up from the centre and secured in a bundle with a strap.

Steel Band. For large surveys, where the repeated use of a chain might introduce a considerable error, a steel band is used. This consists of a graduated steel band fitted with brass handles. It may be used, instead of a chain, in the normal way and is more reliable since the links in a chain may become bent or stretched. The band will also run very smoothly over rough ground, which might catch a chain, but it is liable to snap and must be kept well oiled to prevent rust.

For extremely accurate work, such as setting out a base line for a large survey, a steel band is essential. Under these conditions a small error in the base line might cause considerable inaccuracy at distant points. The steel band is set up under a standard measured pull and corrections are made for temperature and for any difference in level between the two ends of the band. Variations in length due to tem-

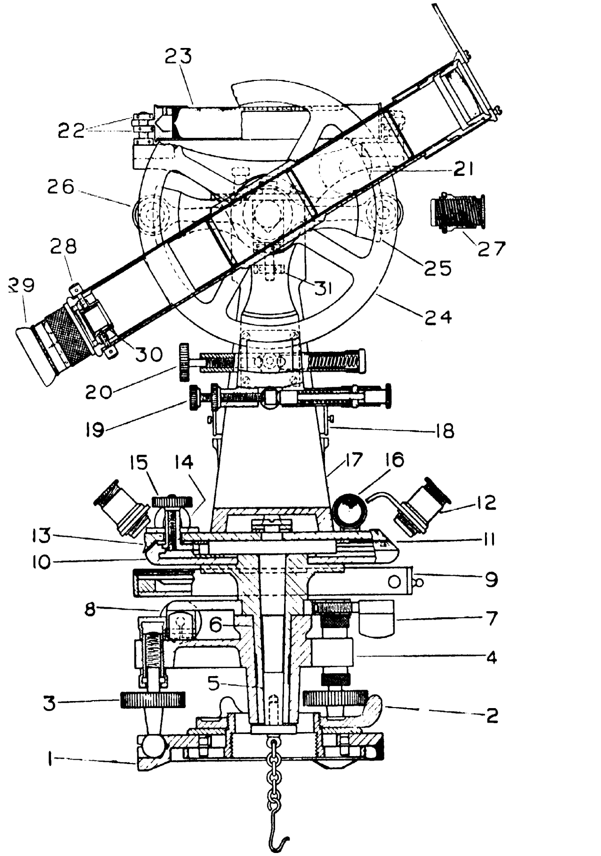


Fig. XXIV. 1. Cross section through theodolite.

1. Lower parallel plate and centring adjustment.
2. Clamp for centring adjustment.
3. Levelling screws.
4. Upper parallel plate.
5. Inner centre.
6. Outer centre.
7. Clamp for outer centre.
8. Tangent screw for bottom plate.
9. Trough compass.
10. Bottom plate of horizontal circle.
11. Verniers.
12. Microscopes for horizontal circle.
13. Vernier plate for horizontal circle.
14. Inner centre tangent screw for setting Vernier plate.
15. Inner centre clamp.
16. Vernier plate bubble tube.
17. Standards.
18. Bubble mounted on standard.
19. Slow motion screw for setting the whole of telescope and verniers.
20. Slow motion screw for setting Verniers.
21. Focusing adjustment for telescope.
22. Circular nuts adjusting bracket level.
23. Bracket level.
24. Vertical circle.
25. Verniers for vertical circle.
26. Microscopes for Verniers.
27. Section showing microscope focusing
28. Screws for adjusting diaphragm.
29. Screw focusing eyepiece.
30. Detachable diaphragm.
31. Rising V for adjusting level of axis.

perature can also be largely overcome by the use of a band of Invar steel which has a very low coefficient of expansion.

Tapes. For plotting the topography from the main survey lines a tape measure is used. Tapes are made in lengths of 33 ft., 66 ft., or 100 ft. and are marked in feet, inches and eighths of an inch on one side and links of a 66 foot chain on the other side. They are made to roll up inside a small leather case. For ordinary measurements a linen tape is used but this cannot be depended upon for accurate measurement because it may stretch, especially in wet weather. A steel tape is used for precise measurement. This is considerably more accurate but snaps easily and must be kept clean and oiled to prevent rust.

Ranging Rods and Arrows. The pegs used to mark survey points are usually not clearly visible from a distance. A ranging rod is used to mark these points when observations are being taken. These rods are iron-shod wooden poles, slightly tapered to the top, which may be 6, 10 or 15 feet high. They are painted in divisions either of 1 foot or ten links, alternately black or red and white. Three such poles can be used to set out a straight line and when chaining, the chainman can keep straight by lining himself in with two of them.

Arrows are used to mark the end of each chain. They are iron skewers about 1 foot long. The man at the head of the chain inserts the arrow in the ground and then drags the chain on. The chainman at the other end finds the arrow and brings his end to it. The arrows are picked up before he moves on and form a check on the number of chains measured.

Measurement of Angles

Theodolite. This instrument is used for the accurate measurement of angles in the horizontal and vertical planes. The diagram (Fig. XXIV. 1) shows details of a typical instrument. It consists of a telescope which is of the normal internal focusing type except that there is a diaphragm carrying cross-hairs or graticules in the eye-piece. These hairs are either etched on a glass plate or consist of fine spiders' web stretched across a brass ring and are adjusted so that the intersection of the cross-hairs lies on the collimation line or optical axis of the telescope.

The telescope is supported at each side by standards so that it can rotate in a vertical plane, its axis of rotation intersecting the collimation line. The angle through which the telescope turns is measured by the vertical circle attached to the telescope axis which is read against verniers, fixed to the standard, with the aid of small microscopes.

The standards are carried on the upper or vernier plate and are high enough to allow the telescope to be turned through a complete circle. The upper plate is horizontal and rotates on a fixed vertical axis which passes through the line of collimation of the telescope. It is free to rotate independently over the lower plate but can be clamped to it by a clamping screw. Fine adjustment of the relative position of the two plates can be made with a tangent screw. The bottom plate is bevelled at the edge to form the horizontal circle which is divided from 0 to 360° and serves to read the relative positions of the bottom and top or vernier plates. Microscopes are provided for reading. The lower plate is also

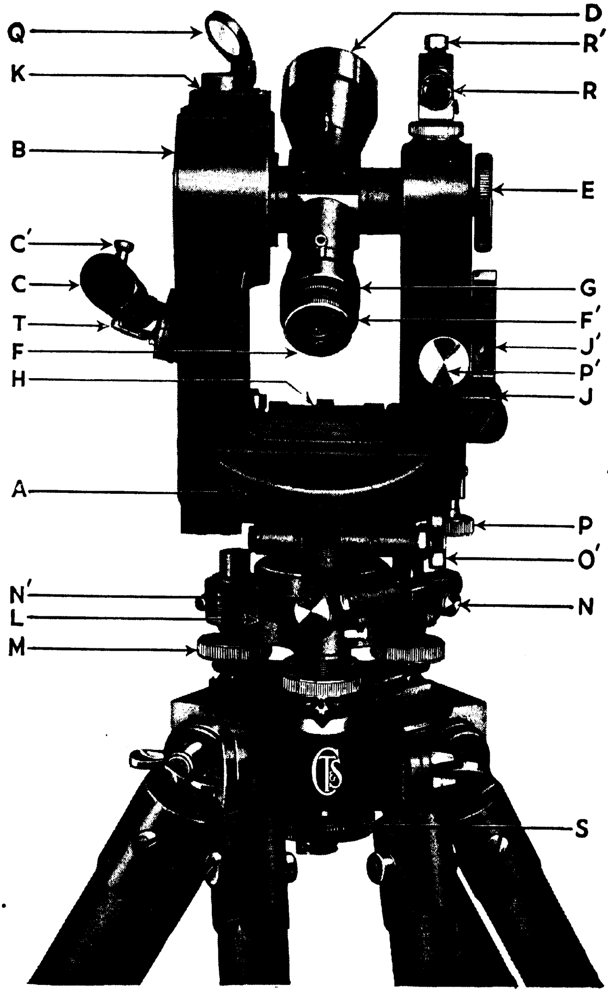


Fig. XXIV.2. Optical scale theodolite.

A. Casing of horizontal circle.
B. Casing of vertical circle.
C. Circle reading eyepiece.
C'. Focusing clamp for circle reading eyepiece.
D. Object glass.
E. Focusing head for telescope.
F. Screw-focusing eyepiece.
F'. Clamping ring for eyepiece focusing.
G. Cover to reticule adjusting screws.
H. Plate spirit level.
J. Line-of-sight spirit level.
J'. Reversible mirror to J.
L. Tribrach.
M. Footscrew.
N. Clamp for lower plate.
N'. Slow motion screw for lower plate.
O'. Slow motion screw for upper plate.
P. Clamp for telescope.
P'. Slow motion screw for telescope.
Q. Illumination reflector for circles.
R. Magnetic compass.
R'. Needle release for compass.
S. Attachment screw and clamp to centring.
T. Lock for circle reading eyepiece.

free to rotate and can be clamped to the axis by a clamping screw and finally adjusted by a tangent screw.

The fixed vertical axis is carried by the upper parallel plate through which pass three levelling screws to the lower parallel plate. These screws allow the instrument to be levelled up on the tripod, with the help of bubble tubes, so that the vertical axis is truly vertical and the upper and lower plates and the axis of rotation of the telescope are horizontal.

The lower parallel plate is arranged to slide bodily within certain limits on the plate of the tripod so that the plumb-bob, which hangs vertically from the centre of the vertical axis, can be brought over the required point on the ground. The instrument is then secured firmly by the clamping ring.

Three bubbles are usually provided for levelling the instrument. A small circular bubble on the upper parallel plate facilitates the setting up of the tripod legs. The levelling of the instrument is done with a sensitive bubble on the upper plate and a further bubble is provided either on top of the telescope or to level the verniers of the vertical circle.

The vertical and horizontal circles are engraved on solid silver inlaid strips to a high degree of accuracy. For precise measurement the verniers may be replaced by micrometer microscopes which enable the circles to be read to 10 seconds and by estimation to 1 second.

The above description covers the ordinary standard instrument but a number of improvements have been made recently, resulting in more compact design and lower weight. The vertical and horizontal circles of one type of instrument are made of glass and light is reflected through them. These circles are found to be more accurate and more easily read than the standard type. A special optical system is provided which allows both circles to be read simultaneously through a small eye-piece beside the telescope. This gives easy and accurate reading and, as the whole instrument is totally enclosed, damage to the circles and other parts due to dust and moisture is avoided. The illustration (Fig. XXIV. 2) shows a typical modern theodolite of this type.

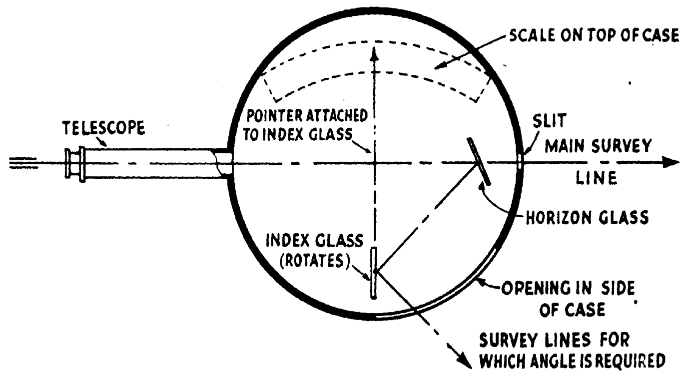


Fig. XXIV. 3. Box sextant. Used for approximate angular measurements.

Box Sextant. For approximate measurement of angles, where the accuracy of a theodolite is not required, the box sextant is very convenient. This instrument consists of a circular box, 3 inches diameter and about 2 inches deep. The optical system (see Fig. XXIV. 3) comprises a telescope, a horizon glass or mirror the upper part of which is not silvered, and an index glass that rotates about a vertical axis and carries a vernier moving over a scale which is calibrated to measure the angle between the survey line seen in the telescope through the clear portion of the horizon glass and the survey line seen reflected into the telescope by the index glass and the silvered part of the horizon glass. Ranging rods placed on the two survey lines will appear one above the other in the telescope and the index glass is rotated until the two images are vertically above each other. The angle can then be read off the vernier to an accuracy of 1 minute.

Cross Staff. A convenient and simple instrument for setting out angles of 90° and 45° is the Cross Staff (Fig. XXIV. 4). This consists of an octagonal box provided with a socket to fit on top of a ranging rod. Slits are cut on opposite sides of the box and, by siting through the appropriate slits, the required angle can be set out.

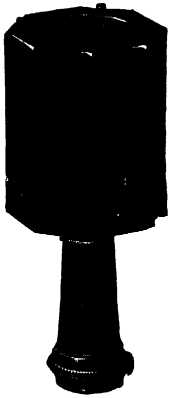


Fig. XXIV. 4. Octagonal cross staff head. Employed for setting out angles of 45° and 90°.

Optical Square. This is an instrument used for setting out right angles. It consists of a small circular box containing two mirrors, one only partly silvered. The optical arrangement is shown in the diagram (Fig. XXIV. 5). A ranging rod on the main survey line is sighted through the clear part of the horizon glass and a second rod seen, reflected from the second mirror, in the lower, silvered, part of the horizon glass is moved until it appears to coincide with the first. The second rod then lies on a line at right angles to the main survey line.

Levelling

Dumpy Level. Essentially this level consists of a telescope, with a diaphragm carrying horizontal and vertical cross-hairs in the eye-piece, mounted on a vertical axis carried on a tribrach with three footscrews as shown in the

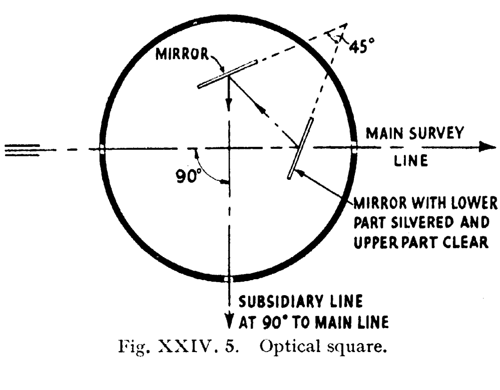


Fig. XXIV. 5. Optical square.

illustration (Fig. XXIV. 6). The footscrews bear on the lower plate or trivet which can be mounted on a tripod but has feet cast on its under side so that the instrument can be used on any flat surface without a tripod if desired. A very sensitive bubble tube is attached to the telescope and is so adjusted that when the bubble is central the collimation line of the telescope is horizontal. In use the three footscrews are adjusted until the bubble remains central whichever

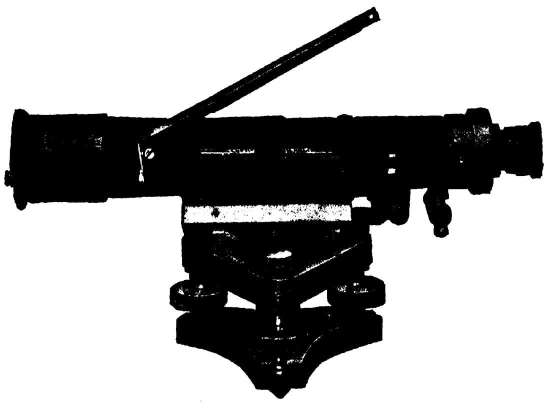


Fig. XXIV. 6. Dumpy level. Standard model with internal focusing telescope.

way the telescope is turned. The line of sight through the telescope will then be horizontal for any position of the telescope and the difference in level between any two points can be found by reading on a levelling staff held at each point the height from ground to sight line. The difference between the two staff readings represents the difference in level of the two points.

Self-Adjusting Level. Setting up a Dumpy Level is a fairly long and tedious procedure as it is difficult to get the bubble to remain central for all positions of the telescope. In the self-adjusting type of level (Fig. XXIV. 7) the telescope is brought roughly level using the foot-screws and a small circular spirit level on the tribrach and the final levelling of the main bubble on the telescope is effected by a micrometer screw which tilts the telescope independently of the vertical axis. This final levelling must be repeated for every sight but can be done very rapidly and there is a great saving of time on the initial setting up. The setting is also more accurate since the telescope is brought truly horizontal for each sight.

Quickset Level (Fig. XXIV. 8). This is a variant of the self-adjusting type of level with the vertical axis mounted on a ball and socket mounting instead of the usual three foot-screws. With the aid of a circular bubble the axis can be brought approximately vertical very rapidly and the final levelling of the telescope is done for each sight with a micrometer adjusting screw as in the self-adjusting level.

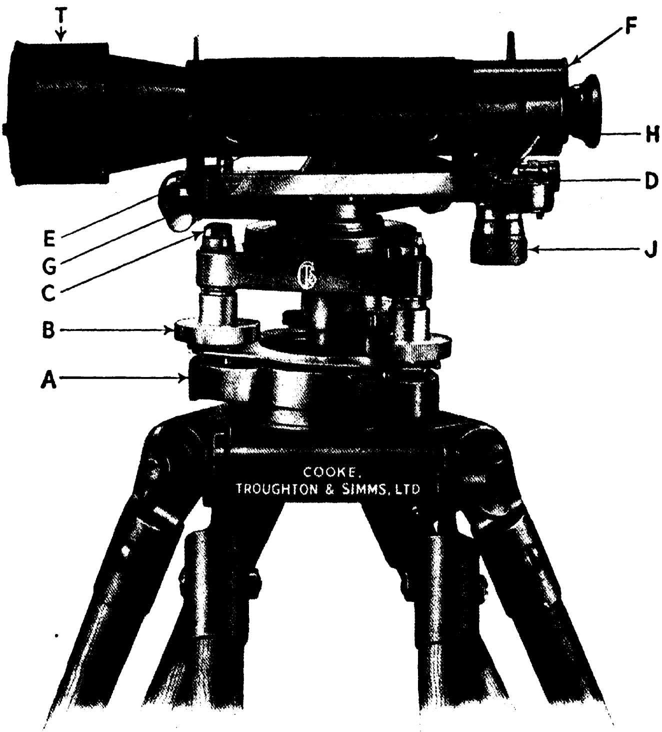


Fig. XXIV. 7. Self-adjusting level.

A. Trivet stage.
B. Levelling screws.
C. Adjusting nut for levelling screws.
D. Circular spirit level.
E. Guard protecting main spirit level.
F. Reading eyepiece for main spirit level.
G. Reflector for main spirit level.
H. Adjusting screws for main spirit level (not seen).
J. Fine levelling screw and gradienter.

Optical Micrometer. For very accurate work a good precision level can be fitted with an optical micrometer with which levels may be read to one thousandth of a foot and estimated to one ten-thousandth of a foot. The device consists of an optically-worked parallel disc of glass horizontally pivoted in a tubular mount in front of the object glass of the telescope. The disc can be rotated and its movement is measured by an arm moving over an arc of twenty equal divisions of such a size that when the arm moves through twenty divisions the amount of tilt given to the glass disc displaces the line of sight by exactly 0.02 feet. The new line of sight remains absolutely parallel to the collimation line of the telescope as can be seen from the diagram (Fig. XXIV. 9), and the micrometer is therefore independent of the length of the sight.

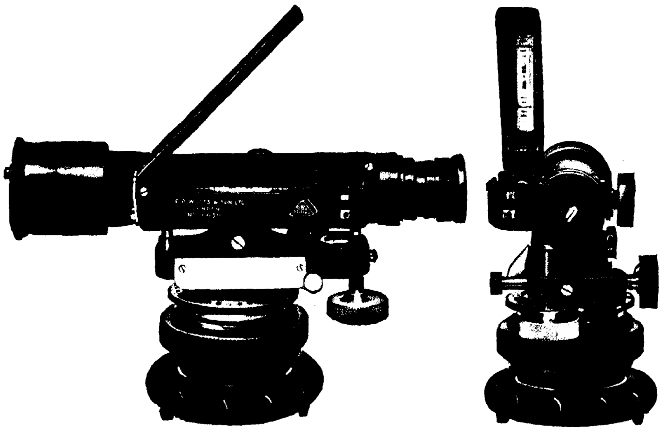
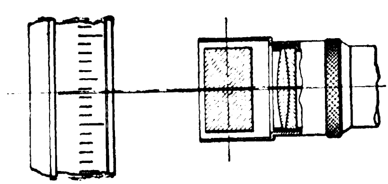
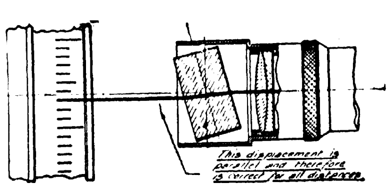


Fig. XXIV. 8. Quickset level. A ball-and-socket mounting, instead of the usual levelling screws, enables preliminary levelling to be carried out speedily.



(a) Normal position (no displacement).



(b) Parallel displacement through refraction.

Fig. XXIV. 9. Optical micrometer permitting precision levels to be read to 1/1,000th ft. and to be estimated to 1/10,000th ft.

Hand Level. Where accuracy need not be great a hand level may be used. It consists of a tube with a horizontal crosswire and a half-silvered mirror arranged so that the levelling staff can be observed through the clear part and the position of a bubble mounted on top of the tube can be seen reflected in the silvered part. The instrument is held on top of a five-foot ranging rod and is tilted until the image of the bubble, seen in the mirror, is central. The crosswire reading on the levelling staff is taken and the difference between staff reading and the height of the rod on which the instrument is held is the difference in ground level at the staff and the instrument.

Levelling Staffs. In levelling, the height of the collimation line of the instrument above the point, for which the level is required, is determined by finding the reading on a special levelling staff which coincides with the crosswire of the instrument. The telescopic staff (of the type shown in Fig. XXIV. 10) is most commonly used and consists of three sections which slide inside each other and when fully extended have a total height of 14 feet. Special scales are used on the face of the staff, the most common being the Standard Upright Sopwith Scale divided in feet, tenths and hundredths of a foot. The figures indicating feet are usually painted red and the others black.

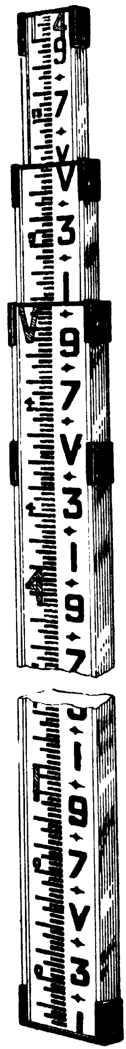


Fig. XXIV. 10. Standard Upright Sopwith Levelling Staff.

Tacheometry

Tacheometry is a method of measuring lengths by optical means. This is a great advantage in rough country and provides a method of obtaining reasonably accurate measurements rapidly. The Tacheometer is identical with an ordinary theodolite except that two additional cross-wires, known as stadia wires, are set horizontally in the eye-piece. An ordinary levelling staff is held at the point for which the distance from the instrument is required and the readings of the two stadia wires are observed. The distance can be calculated from the difference between these two readings and the constants of the instrument.

The diagram (Fig. XXIV. 11) explains the principles involved. If s is the difference between the staff readings, i the distance between stadia wires, f_1 the distance from the stadia wires to the object glass, and f_2 the distance from the object glass to the staff, then by geometry $f_2 = f_1 . s/i$, and if d = distance from object glass to the axis of the instrument then

Distance from axis of instrument to staff

$$= D = f_2 + d$$

Now f_1 will vary with the focusing of the object glass, but from the properties of lenses

$$\frac{1}{f_1} + \frac{1}{f_2} = \frac{1}{f}$$

where f = the focal length of the object glass.

$$\text{Hence } f_2 = (f.f_2/f_1) + f = \frac{f\,s}{i} + f$$

$$\text{And} \quad D = \frac{f\,s}{i} + (f + d) = k.s + (f + d)$$

The values of k, usually 100, and $(f + d)$ are given by the manufacturers. Note that d varies according to the focusing to the extent of about 1 or 2 inches and is therefore a determining factor in the accuracy

of measurement. By using an anallatic lens in the telescope, the additive constant $(f + d)$ can be eliminated and the formula becomes $D = k.s.$

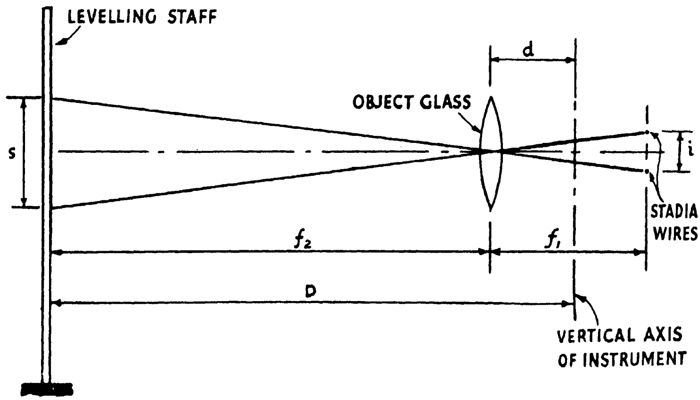


Fig. XXIV. 11. Optical system of a tacheometer.

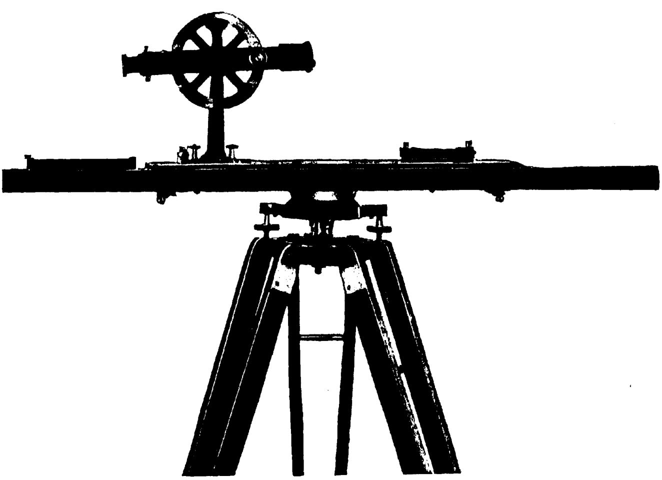


Fig. XXIV. 12. Plane table.

Plane Table

With the plane table (Fig. XXIV. 12) a survey can be plotted immediately in the field. The table is a drawing board, mounted on a levelling device on a tripod, on which a piece of drawing paper can be pinned. On the paper is placed the Alidade, which is similar to the upper part of a theodolite but is mounted on a brass rule instead of on the horizontal circles. A point is selected on the drawing paper to represent

the location of the instrument, the edge of the alidade is placed against it and the telescope pointed towards a topographical feature. A ray is drawn on the paper along the edge of the alidade showing the direction of the feature and its distance may be found either by using an alidade fitted with tacheometric stadia, or else by setting up at another known station and drawing a second series of rays to intersect the first.

The method is very useful for rapid filling in of detail from the main survey points but is of course impracticable in bad weather.

Photographic Surveys

If a photograph is taken from a survey point with a camera, mounted so that it is horizontal, fitted with collimating marks to indicate the position of the optical axis of the camera on the picture, then, if the focal length of the camera is known, the photograph can be used to plot a series of rays giving the direction from the survey station of all points whose position is required. Another photograph of the same area taken from a second survey station will provide another series of rays which will fix the position of every point providing the directions in which the two photographs were taken are known. The method can be used to obtain levels and contours as well as topographical details if the level of the optical axis of the camera at each set up is known. Survey work of this kind can also be carried out with the optical axis of the camera vertical or inclined at a known angle. The illustration (Fig. XXIV. 13) shows a Photo-theodolite which automatically records on the photograph all the information required for plotting, such as the position of the axes and the bearing of the line of sight.

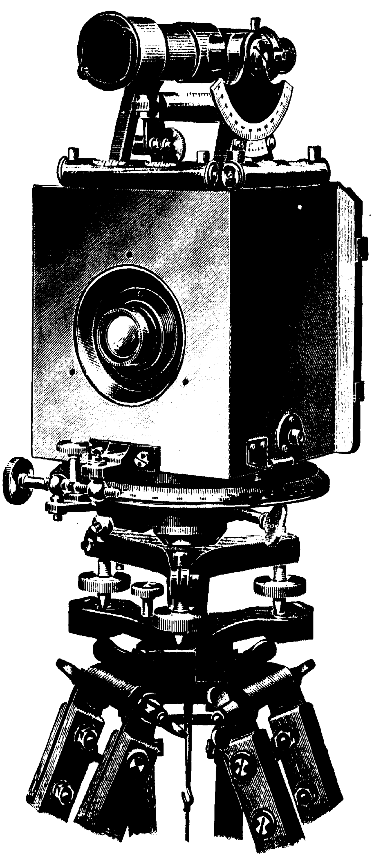


Fig. XXIV. 13. Photo-Theodolite.

Stereoscopic methods are also used in which two photographs are taken from different stations, as in the previous method, but the optical axis of the camera is set perpendicular to the line joining the survey stations for both exposures instead of the angle

varying. When viewed through a stereoscope a pair of these photographs will give a picture which appears to be three-dimensional. An instrument known as the Stereo-comparator has been devised which allows detailed measurements to be taken from a stereoscopic pair of photographs with the aid of which a survey can be plotted. A further elaboration is the stereo-autograph which is designed to plot the information automatically. To obtain the stereoscopic pictures an ordinary Photo-theodolite is used in ground survey work. For aerial work special cameras have been devised which take pictures at regular intervals and record automatically the bearing, altitude, picture number, and tilt of the aircraft.

SECTION 4

LIQUID TESTING

CHAPTER XXV

VISCOSITY MEASUREMENT

Viscosity is of importance wherever the flow of fluid occurs. One part of a stream of fluid may move more rapidly than the portions adjoining it, as for example in a pipe where the liquid in contact with the wall will be at rest but that in the centre will be travelling at maximum speed. Wherever this difference in velocity occurs it is found that there is a drag between adjoining parts of the fluid, the faster-moving layers tending to speed up the slower and being themselves slowed down. This effect is due to viscosity and has a resemblance to the friction which occurs between solid surfaces. The actual drag per unit area between adjacent layers varies inversely as the distance between them and directly as their relative velocities, but it is also dependent on the nature of the fluid. This last factor is introduced into the relationship in the form of a coefficient of viscosity which varies according to the fluid and is also dependent on the temperature.

Definition of Viscosity and Units of Measurement

Dynamic Viscosity. The coefficient of dynamic viscosity of a fluid, denoted by η, is defined as the force per unit area required to maintain unit difference of velocity between two parallel planes unit distance apart when the intervening space is filled with the fluid in question. If a force of one dyne is required to maintain a velocity difference of one centimetre per second between two planes one centimetre apart, the fluid is said to have a viscosity of one poise. One hundreth part of a poise is known as a centipoise.

Kinematic Viscosity. In certain problems it is convenient to use the kinematic viscosity, denoted by ν, which is defined as dynamic viscosity divided by the density of the fluid. The unit of kinematic viscosity is the Stokes. The kinematic viscosity in Stokes is equal to the dynamic viscosity in poises divided by the density in grammes per cubic centimetre. The centistoke is one hundredth part of a Stokes.

Technical Units. Certain arbitrary scales of viscosity have been established for technical use depending on the type of viscometer employed. Thus the Redwood instrument measures viscosity in Redwood seconds. These scales can usually be related to the absolute units given above.

Standard U-Tube Viscometer, B.S.S. No. 188-1937

This instrument is a standard viscometer for liquids where the kinematic viscosity does not exceed 1,500 centistokes. As shown in

the diagram (Fig. XXV. 1) the U-tube is reduced to a capillary tube for part of one limb. Above this capillary are two bulbs BC and CD and marks are engraved on the tube at B and C. The other limb has a bulb GF and a mark is engraved above this bulb at G. In use the U-tube is filled through the arm HG, taking care to avoid air bubbles, until the liquid in this arm stands within 0.2 millimetres of the mark G when the tube is vertical and the correct temperature has been reached in the surrounding water bath. The liquid is then blown or sucked to a point 1 centimetre above the mark B, care being taken to prevent any moisture entering the tube. The liquid is now allowed to flow freely and the time taken for the meniscus to fall from the mark B to mark C. From this time the viscosity can be calculated using the formula:

Kinematic viscosity $= C\,t - c/t$

where t is the time for the meniscus to fall from B to C.

· C and c are constants of the instrument.

A standard liquid is used to calibrate the tube.

The British Standard Specification describes various forms of U-tube to cover a large range of viscosities and also for liquids which are opaque and wet glass, thus making accurate observation of a falling meniscus difficult. The small bulb below C is provided so that when the level of the liquid is at C the level in the other arm is still in the cylindrical portion of the bulb GF.

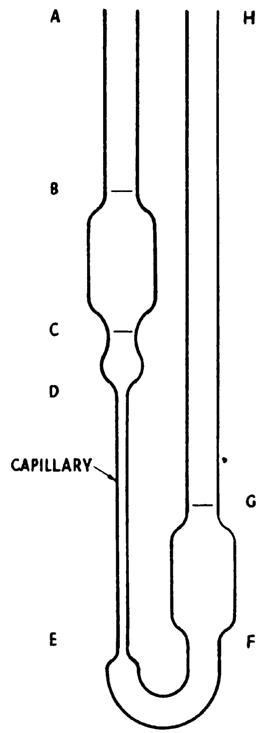


Fig. XXV. 1. Standard U - tube Viscometer (B.S.S. No. 188-1937). Arm HG is filled with liquid to within 0.2 mm. of G. The liquid is sucked up to about 1 cm. above B and then allowed to flow freely. The time is taken for the level to fall from B to C.

Searle's Concentric Cylinder Viscometer

This apparatus consists of a hollow cylinder inside which another cylinder is free to rotate. The annular space between the two cylinders is filled with the liquid for which the viscosity is required. The outer cylinder is clamped to a supporting pillar the top of which acts as the bottom bearing for the axis of the inner cylinder (Fig. XXV. 2). By moving the outer cylinder up or down the pillar the length of the inner cylinder immersed in the liquid can be varied. A perforated plate is fixed to the top of the pillar and fits loosely in the

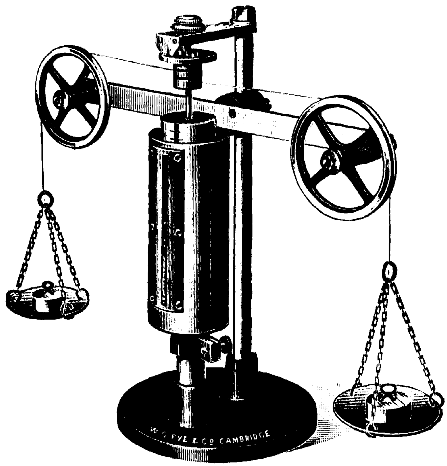


Fig. XXV. 2. Searle's concentric cylinder viscometer.

outer cylinder, its purpose being to prevent the liquid below it being disturbed when the inner cylinder revolves. It thus ensures that the drag on the end of the inner cylinder will be the same whatever the position of the outer cylinder. A couple is applied to the inner cylinder by means of two known weights attached to threads wound round a drum on its axle. The number of revolutions made by the drum can be counted by observing the passage of a mark, on a plate attached to the axle, past a fixed pointer.

The viscosity of the liquid will cause a drag on the rotation of the inner cylinder under the applied couple, and this drag will increase as the speed of rotation increases until the retarding moment due to the drag just equals the applied couple. The speed of rotation will then be constant and it can be shown that:

$$\eta = \frac{G\,T\,(R_2^2 - R_1^2)}{8\pi^2 R_1^2 R_2^2 (L + k)}$$

where η = Coefficient of dynamic viscosity.
G = Applied couple in dyne.cms.
T = Time in secs. for one revolution of inner cylinder.
R_1 = Diameter of inner cylinder in cms.
R_2 = Internal diameter of outer cylinder in cms.
L = Length of cylinder immersed in the liquid in centimetres.
k = Correction for end drag.

The correction k is due to the end drag between the bottom of the inner cylinder and the perforated plate on top of the pillar. By taking two sets of readings using different lengths of cylinder immersed, the end correction k can be found and substituted in the formula given above which will then give correct absolute values of dynamic viscosity.

McMichael Torsion Viscometer

This is a commercial form of the Concentric Cylinder Viscometer. The liquid is contained in a rotating cup (Fig. XXV. 3) driven by an electric motor through a two-speed gear box giving a maximum speed of 40 and 120 revolutions per minute respectively. A cylinder is suspended in the cup from the end of a wire which is clamped at its upper end. The viscous drag of the liquid in the rotating

cup upon the cylinder is balanced by the torsional resistance of the wire. The angular displacement of the ends of the wire due to torsion is read off on a graduated dial. Then, knowing the motor speed and the dimensions of the instrument, the viscosity of the sample can be calculated. The instrument is provided with means of controlling the temperature of the liquid in the cup.

A special advantage of this type of viscometer is its wide range which has a lower limit only slightly above the viscosity of water. It can be used for testing materials whose viscosity cannot be determined conveniently, if at all, by flow type viscometers, for example asphalts, chocolate solutions, and paints.

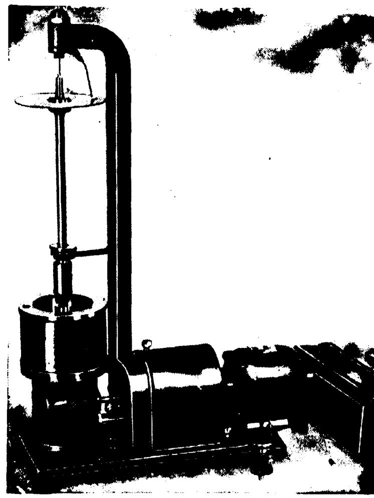


Fig. XXV. 3. McMichael torsion viscometer. A robust commercial instrument with a wide range. Especially suitable for creams, paints and heavy oils.

Falling Sphere Viscometer, B.S.S. No. 188-1937

Stokes showed that a sphere impelled by a constant force F in a viscous liquid eventually assumes a constant velocity V such that:

$$F = 6\pi\eta r V$$

where η = Dynamic viscosity of liquid
r = Radius of sphere.

Thus if the speed at which a small sphere falls through a liquid under its own weight is measured, the viscosity of the liquid can be determined.

The dimensions of the instrument (Fig. XXV. 4) are specified in the British Standard Specification (No. 188-1937). The liquid to be tested is contained in a tube, surrounded by a water jacket, the internal diameter of the tube being not less than ten times the diameter of the sphere used. Reference marks are engraved on the tube 150 millimetres apart and each is not less than 55 millimetres from the ends of the tube. The sphere is usually a steel ball of a

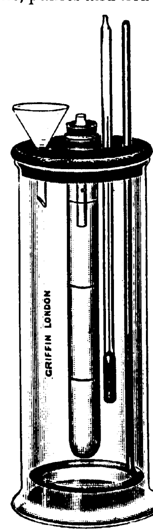


Fig. XXV. 4. Falling sphere viscometer (B.S.S. No. 188-1937). Suitable for liquids having a viscosity of between 1,000 and 25,000 centistokes.

diameter suitable to the viscosity of the liquid. The diameter ranges from $\frac{1}{16}$ inch (1.59 mm.) for liquids of kinematic viscosity from 1,000 to 5,000 centistokes to a diameter of $\frac{1}{8}$ inch for viscosities from 12,500 to 25,000 centistokes.

The tube is filled with the liquid to be tested and left, vertically, in the water jacket for at least one hour at test temperature. The sphere is then introduced axially into the liquid by means of a short tube, which can be seen in the figure, and the time is taken for its passage from one mark to the next. In calculating the viscosity it should be remembered that Stokes' Law, given above, is only true if the liquid is of infinite extent. Allowance must therefore be made for the drag set up between the sphere and the wall of the tube through the intervening liquid. Taking this into account, the British Standard Specification gives the formula:

$$\text{Kinematic viscosity } \nu = \frac{t\,d^2\,g}{0.18\,s}\left(\frac{\delta}{\rho} - 1\right)\left(1 - 2.1\,\frac{d}{D}\right)$$

where g = 981 cm./sec^2.
d = Diameter of sphere in cms.
δ = Density of sphere in grammes/cubic cm.
ρ = Density of liquid under test in gms./cubic cm.
s = Distance between reference marks.
t = Time for sphere to fall from one mark to the other.
D = Diameter of tube in centimetres.

This can be simplified to:

$$\nu = K\,t\left(\frac{\delta}{\rho} - 1\right)$$

where K will be a constant as long as the same sphere and tube are used.

Redwood Viscometer, B.S.S. 148-1933

The rate of flow of a liquid through a short tube is dependent upon its viscosity. This is applied in the Redwood Viscometer which uses the time required for a given volume of liquid to flow through a standard orifice, as a measure of viscosity.

A vertical cylinder, with a standard agate orifice (Fig. XXV. 5) fitted in the centre of its base, contains the liquid to be tested. Round this cylinder is a water jacket provided with thermostatic control to maintain the liquid at the desired temperature. The orifice is closed and the inner cylinder is filled to a standard height with the liquid to be tested. When the temperature is correct the orifice is opened and the time taken for 50 cc. of the liquid to flow into a measuring flask. This time in seconds is the "Redwood Viscosity."

Two models of this instrument are made, the No. 1 type is used for lubricating oils at the normal range of temperatures, whilst the No. 2 instrument is used for oils of high viscosity or for low temperature measurements, in which case the water jacket can be packed with ice.

Ford Cup Viscometer

This is a general utility instrument used by the Ford Motor Co. for determining the viscosity of oil. Its simplicity and robust construction have, however, brought it into general favour. It

consists of a brass cup with an annular overflow trough at the top and a standard orifice in the bottom. After levelling the instrument the orifice of the cup is closed and oil poured in until it overflows into the trough. The oil must be free of air bubbles and the surface should be swept off level with a steel rule. The orifice is opened and a stop clock started at the same moment. The whole contents of the cup is allowed to flow out and the clock is stopped at the first evidence of the stream of oil breaking up into drops. This time is the viscosity measured in Ford seconds. No water jacket is provided and if the viscosity is required at temperatures above that of the laboratory the oil and cup are heated about one or two degrees above the required temperature and the test made when the cup has cooled to the correct value. Four sizes of orifices are available according to the materials to be tested. No. 1 viscometer has $\frac{1}{16}$ inch orifice for use with spirit solvents, No. 2 a $\frac{3}{32}$ inch orifice for light lacquers, No. 3 a $\frac{1}{8}$ inch orifice for light oils, and No. 4 has a $\frac{5}{32}$ inch orifice for heavy oils.

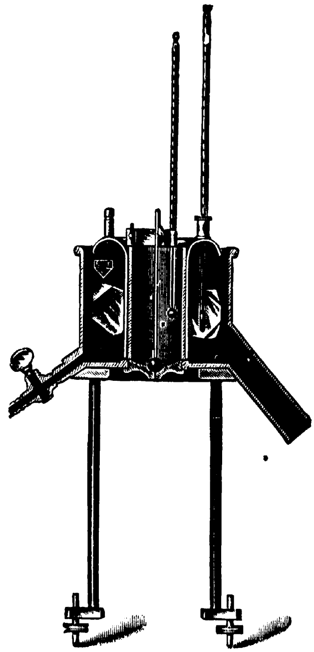


Fig. XXV. 5. Redwood Viscometer No. 1. Sectional view of standard model, arranged for gas heating, conforming to the specification of the Institution of Petroleum Technologists and B.S.S. No. 148-1933.

Engler Viscometer, B.S.S. 618-1935

This is similar to the Redwood instrument, consisting of an oil cup with a short tube jet at the bottom. The cup is wider and shallower than the Redwood and care must be taken in filling it correctly and levelling it. A lid is provided to the cup and the whole is enclosed in a water bath. In performing the test the cup is filled to a standard mark and, when the liquid has reached the desired temperature, the time of outflow of 200 cc. is taken. The viscosity can then be expressed in either of two ways, either as the time of outflow in seconds (Engler seconds) or that time divided by the time for outflow of 200 cc. of water (Engler degrees).

Saybolt Universal Viscometer

This is the United States Government standard instrument and is similar in type to the Redwood and Engler viscometers. The initial setting of the liquid level is made by completely filling the cup until it flows into a channel round its upper edge. The cup is surrounded by a water bath which is thermostatically controlled. When the liquid has

reached the required temperature it is allowed to flow through a standard orifice. The time taken for the first 60 cc. is used as a measure of viscosity.

Michell Viscometer

A very simple and ingenious commercial viscometer consists of a steel ball fitting into a steel cup. Complete contact is prevented by three small projections on the inner surface of the cup, which keep the ball a fixed distance from its surface. A few drops of the oil to be tested are put in the cup and the ball is placed in position, care being taken to eliminate all air between the two surfaces. The cup is then inverted and cup and ball are pressed on a hard surface to ensure close contact with the projections. The cup is lifted vertically with the ball suspended from it and the time is taken from the moment of lifting to the moment

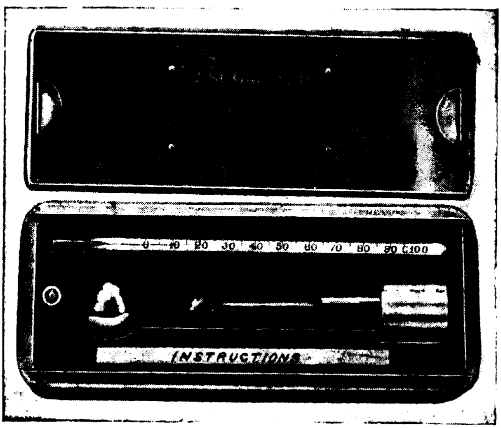


Fig. XXV. 6. Michell Viscometer. A commercial Cup and Ball instrument suitable for testing oils and varnishes.

the ball detaches itself from the cup. This time is a measure of the viscosity of the oil filling the space. For tests at high temperatures the cup and ball are heated to the required degree which is indicated by a thermometer in the handle of the cup. As the amount of material in the ball and cup is comparatively large, the temperature will not drop appreciably during the test. Fig. XXV. 6 shows the instrument which fits compactly into a small pocket case.

"Dobbie McInnes" Ball and Bucket Viscometer

This instrument measures viscosity by finding the time taken for a heavy "bucket" to fall clear of a fixed "ball" when the bucket is filled with the liquid to be tested. Special features of the instrument are the elimination of the human element in timing and the accurate control of temperature. The bucket is filled with the oil and is brought into

position so that the ball touches the bottom of the bucket and is completely immersed in the liquid. The release of a trigger allows the bucket to drop and at the same instant operates a stop-clock. When the bucket falls clear the clock is automatically stopped. The whole of the working parts are surrounded by a thermostatically-controlled paraffin bath which maintains the oil and the ball and bucket at the desired temperature.

Vogel-Ossag Viscometer

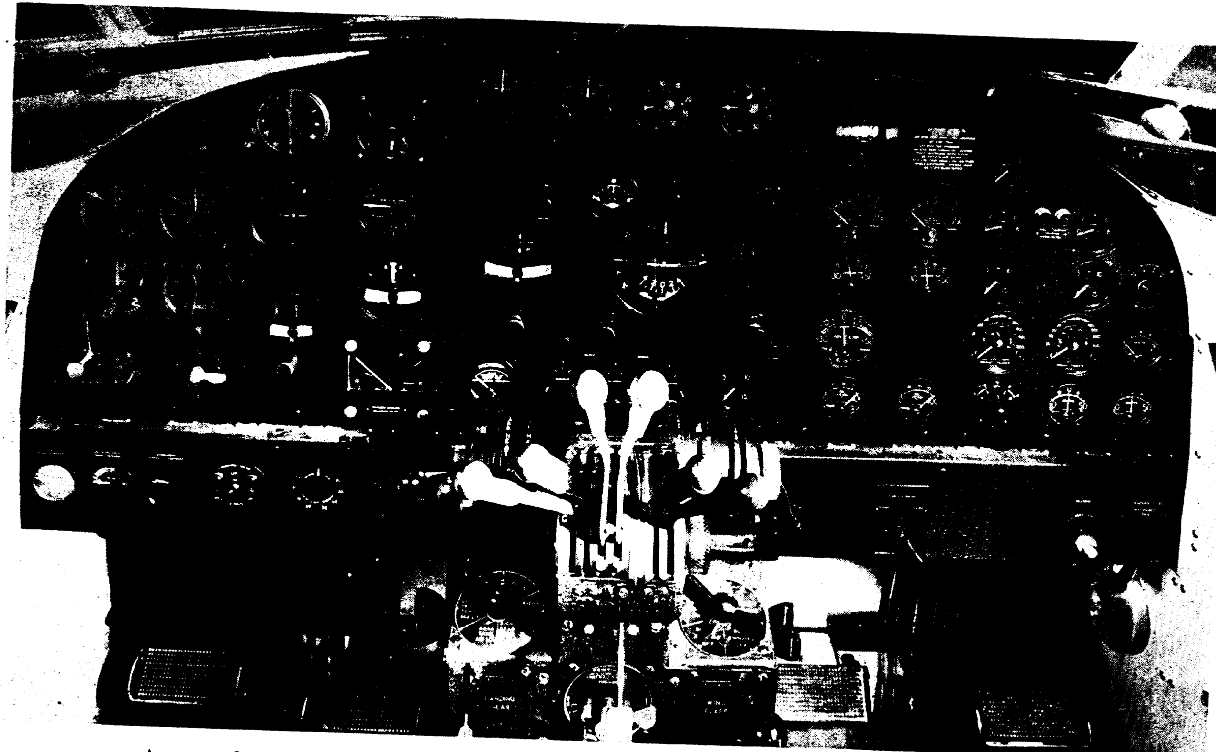
This is a pipette type of viscometer consisting of a capillary tube sealed to a bulb provided with two graduations placed so that a known volume of liquid is discharged through the capillary as the level falls from one mark to the other. The time required for this discharge to take place is a measure of the kinematic viscosity of the liquid.

The special feature of the Vogel-Ossag instrument is that the end of the capillary is submerged in a cup to a fixed depth. An overflow trough is provided around the cup and as the liquid flows from the bulb the cup overflows, thus ensuring that there is no alteration of the back pressure on the capillary due to the liquid in the cup. This arrangement also allows of the whole instrument being completely surrounded by a water jacket since no opening is required, as in the Redwood type of instrument, for the jet of liquid to discharge into the open air. Another advantage is that only 15 cc. of the liquid to be tested are required as against 50 cc. for the Redwood and 200 cc. for the Engler instruments.

Gardner-Holdt Bubble Viscometer

The speed at which a bubble of air will rise in a tube containing a liquid depends upon the viscosity of the liquid. This fact is used in the Gardner-Holdt viscometer which comprises a range of 20 sealed glass tubes each completely filled with mineral oil except for a small air bubble. The viscosity of the oil increases from tube to tube, each tube being marked with the appropriate viscosity. The liquid, for which the viscosity is to be found, is placed in a similar tube, leaving an air bubble of the same size. The time taken by the air bubble to rise in the sample under test can be compared with any of the standard bubble tubes simply by holding the two tubes side by side, inverting them and watching the bubbles rise to the top. In this way two standard tubes can be found, in one of which the bubble rises more rapidly and in the other more slowly than in the sample under test. The viscosity of the unknown sample will lie between the viscosities given for these two standard tubes. Tests can be carried out at various temperatures by conducting the operations in a water bath.

The oils used in the standard tubes are specially chosen so that there will be no appreciable change in their viscosity with age. Two sets, each of 20 tubes, are made, one covering viscosities from 0.5 to 5.5 poises and the other from 6.27 to 148 poises.



An example of modern applications of scientific instruments. The control panels of an aeroplane on which many of the instruments and principles explained in this book are employed.

SECTION 5

MISCELLANEOUS

CHAPTER XXVI

ACOUSTICS

Acoustics is the study of the behaviour and properties of sound. It is of primary interest to every member of the community, for it concerns such varied matters as the reproduction of sound by the gramophone, radio and sound film, the acoustic properties of theatres and buildings, and the control and suppression of noise. Great advances have been made in this subject in recent years and, as in every other science, accurate measurement has played a large part in this development.

Sound waves are set up by vibrating bodies and are longitudinal waves, consisting of alternate condensations and rarefactions, which have a velocity depending upon the density and elasticity of the medium in which they travel. In air this velocity is about 1,100 feet per second. Reflection, refraction or absorption of the waves will occur when sound passes from one medium to another, the behaviour being analogous to that of light.

Two main types of measurement are required in the study of acoustics. The first group comprises the fundamental properties of the sound wave itself, its frequency and intensity. The other, which might be said to deal with applied acoustics, deals with the behaviour of sound waves in given surroundings and their reflection and absorption by different materials.

Measurement of Frequency

When sound is propagated in a medium, the particles of the medium are displaced and go through a series of movements which repeat themselves at regular intervals. A complete series is known as a cycle and the number of repetitions of this cycle made by a particle in the medium in unit time is called the frequency of the sound, and is usually measured in cycles per second.

Absolute Measurement of Frequency. To set up acoustical standards of frequency absolute measurements must be made. The operation consists of measuring the number of vibrations occurring in a measured time. A tuning fork is a well-known standard and may be calibrated in the following way. A very fine bristle is attached to one prong of the fork and allowed to bear on the smoked surface of a drum which revolves at a constant known speed. The vibration of the prong will draw a wave on the surface of the drum from which the distance moved through by the drum during one complete vibration of the prong can be found. From this distance and the known speed of the drum, the time of one vibration and therefore the frequency of the tuning fork can be calculated.

Comparative Measurement of Frequency. Once an absolute standard of frequency has been established, such as a tuning fork, it is often more convenient to determine the frequency of other sounds by comparison with the standard. Electrical methods are freely employed, the sound being converted into electrical vibrations by means of a microphone and

amplifier. Standard electrical frequencies can be conveniently produced by means of an audio frequency oscillator which may be calibrated against an absolute frequency source by the cathode ray oscillograph method described below.

String Oscillograph. A string oscillograph having two elements may be employed for frequency measurement by actuating one element from a source of known frequency and the other element from a microphone receiving the sound of unknown frequency. The two frequencies are recorded on the same film and can be conveniently compared.

Cathode Ray Oscillograph. If the known and unknown frequencies are applied to a cathode ray oscillograph, so that the displacement caused by one is at right angles to that produced by the other, patterns will be produced on the screen, which are known as Lissajou's figures. Where a simple ratio connects the two frequencies definite stationary figures are produced, the shape of the figure depending on the ratio of the frequencies. Thus from a knowledge of the various figures and the frequency of the standard source the unknown frequency may be determined. This method is useful for the calibration of an audio frequency oscillator against a single absolute standard. The input from the standard source is arranged to cause displacement in one direction and that from the oscillator in the other direction. The frequency of the oscillator is then adjusted to produce the various figures in turn and the oscillator control reading is plotted against the appropriate frequency to obtain a calibration curve. Considerable accuracy can be obtained since if the oscillator frequency is not absolutely correct the figure will start to move on the screen. Once calibrated, the oscillator provides a convenient standard source of sounds of known frequencies.

Method of Audible Beats. A continuously variable source of known frequencies such as the audio frequency oscillator can be used to determine the frequency of an unknown sound by using it to produce a sound of approximately the same frequency. If the known and unknown sounds are heard together, regular "beats" will be heard, the frequency of the beats depending upon the difference in frequency of the two sounds. The frequency of the oscillator can now be adjusted to decrease the number of beats per second until when the two frequencies are identical the beats cease. Reference to the calibration curve of the oscillator will give the frequency of the unknown sound.

Resonators. When the frequency of a sound corresponds with the natural frequency of the air in a vessel resonance occurs and a reinforcement of the sound is obtained. This effect can be used to measure frequency. A resonator consisting of a cylinder fitted with a piston is placed near the source of sound and the piston is adjusted until reinforcement of the sound is obtained. The frequency of the sound is then equal to the natural period of the resonator, which can be calculated from the piston setting.

Measurement of Sound Intensity

Sound intensity is defined as the rate of flow of sound energy per unit area normal to the direction of propagation of the sound wave. It is, however, often considered in terms of the amplitude of the pressure, displacement or velocity variations set up in the medium as a result of

the propagation of the sound wave. The intensity in energy units is proportional to the square of the displacement, pressure or velocity amplitudes.

Units of Measurement. Absolute measurement of sound intensity is made in ergs per second per sq. cm. or micro-watts per sq. cm. but the unit which is, perhaps, used most extensively is the Bel or its subdivision, the Decibel. This is a relative measure of intensity in energy units on a logarithmic scale. Two sounds of intensity I_1 and I_2 in energy units have a difference in intensity of 10 $\log_{10}$ (I_1/I_2) decibels, or if measurements are made in terms of displacement, pressure or velocity amplitudes and are P_1 and P_2 respectively, then the difference in intensity is 20 $\log_{10}$ (P_1/P_2) decibels. This scale is adopted because, in perceiving changes of intensity with the human ear, it is not the actual increase in sound energy that matters but the fractional increase. The decibel is practically the smallest change in intensity that the ear can distinguish.

Rayleigh Disc. A light disc suspended in the path of a sound wave tends to set itself at right angles to the direction of motion of the air particles. If displaced from this position, a turning moment is set up which tends to bring it back. For a disc suspended in a stream of fluid it can be shown that :

$$M = \frac{4}{3}\rho\, a^3\, u^2 \sin 2\theta \quad . \ . \ . \ . \ . \ . \quad (1)$$

where M = Turning moment on disc.
ρ = Density of fluid.
a = Radius of disc.
θ = Angle made by normal to disc with direction of stream.
u = Velocity of stream.

This relationship applies even when the motion of the stream is oscillating, u then being the r.m.s. velocity. The disc must be small compared to the highest wavelength of the sound to be measured, not more than 1 cm. in diameter for frequencies up to 10,000 cycles per second, and is of mica or glass. From equation (1) above it can be seen that the maximum turning moment occurs when $\theta = 45°$ and also that for any given position of the disc M is proportional to u^2. Hence the velocity amplitude of the sound can be determined by measurement of the moment M.

In practice the disc is suspended by a fine quartz fibre about 0.0002 inches diameter and 14 inches long. The back of the disc is silvered and an illuminated scale is arranged so that light is reflected from the disc to a telescope. The disc is set at an angle of 45° to the direction of the sound. On striking the disc, the sound waves will make it rotate slightly, by an amount dependent on the torsional resistance of the quartz fibre. The angle of twist can be determined from the change of scale reading observed in the telescope. If φ is the angle of twist,

$$\varphi = \frac{M}{S}$$ where S = moment of torsion of the suspension,

which may be determined experimentally by observing the periodic time of the disc when allowed to oscillate, the relation being :

$$S = \frac{I}{T^2}\left(4\pi^2 + (\log_e D)^2\right)$$

where $T =$ Periodic time of suspended disc.
$I =$ Moment of inertia of the disc $= m\,a^2/4$.
$m =$ Mass of disc. $a =$ Radius of disc.
$D =$ Damping factor $=$ Ratio of two successive swings.

The value of M thus obtained is substituted in equation (1) from which the velocity u can be found. Care must be taken to shield the disc from draughts.

Hot-Wire Microphone. An electrically-heated grid of very fine platinum wires is placed in the neck of a tunable resonator. The air currents set up in the neck when resonance occurs cool the wires and alter their electrical resistance. From this change of resistance the intensity of the sound can be determined. The instrument is usually used with the mouth of the resonator pointing upwards and must be screened from draughts. It is especially sensitive to low-frequency sounds.

Electrical Microphones. An accurately-calibrated microphone, amplifier and output meter system is the most common and convenient method of measuring intensity. For the majority of purposes the pressure gradient operated ribbon microphone is the most suitable. When calibrated against a Rayleigh disc it shows a smooth response curve practically free of resonance or frequency distortion. Such a system is a great asset for field work as it is portable and robust.

Analysis of Sound

Most ordinary sounds are complex, being made up of a number of components of different frequencies and intensities. To be able to understand and control such sounds it is desirable to split them into their components and to find the intensity and frequency of each part. Most of the methods are electrical and, where the source of sound is not electrical, the audible sound must first be picked up by a microphone.

Electrical Resonance Method. The complex wave is fed to a simple series tuned circuit (Fig. XXVI. 1) consisting of a variable condenser C, an inductance L and a resistance R across which is connected a voltmeter. By varying the condenser C, the circuit can be tuned to any desired frequency component of the complex wave and the current through the circuit will then depend upon the voltage due to the intensity of that component, since by suitable choice of values the "off-tune" resistance of C and L can be made high enough to make the effect of any other component negligible. The intensity is then determined by reading the voltage across the resistance

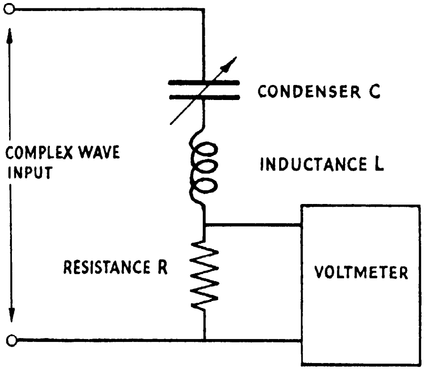


Fig. XXVI. 1. Electrical resonance frequency analyser.

R, which will be equal to the input voltage for the selected frequency.

Heterodyne Method. In this method a variable source of electrical audio frequency is fed in series with the complex sound (Fig. XXVI. 2).

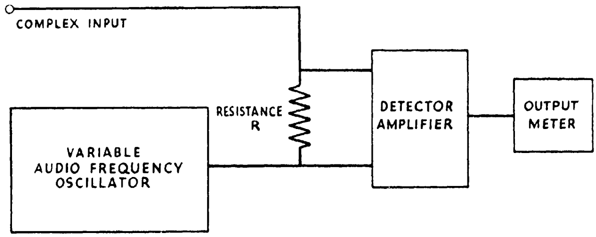


Fig. XXVI. 2. Heterodyne method of wave analysis.

The variable frequency is adjusted to produce beats with the selected component of the complex frequency and the beat frequency is detected by a sharply tuned detector amplifier which will pass only a single frequency of 10 cycles per second. The output of the amplifier is read on an output meter and is proportional to the intensity of the selected frequency component. This method has the advantage over the resonance method of higher selectivity, and one instrument can cover the whole audio frequency range while the resonance method is limited by the size of condenser and inductance used.

Acoustic Spectrometer. A complex sound may be analysed by a series of vibrating reeds. A number of reeds are provided to cover the range of frequencies to be analysed and each reed is tuned so that the fractional increase in resonant frequency from reed to reed is constant. The illustration (Fig. XXVI. 3) shows the arrangement. The complex sound is made to actuate the reeds electrically and the amplitude of

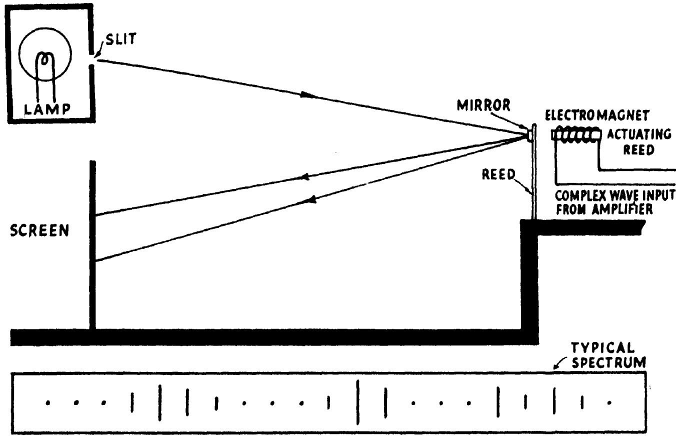


Fig. XXVI. 3. Reed acoustic spectrometer.

vibration of the reed is rendered visible on a screen by the reflection of a spot of light from a mirror on the tip of the reed. Only those reeds whose frequencies are nearest to components of the complex sound will be set in motion and the amplitude of their vibrations will be a measure of the intensity of the components.

Grating Spectroscopy of Sound. High-speed analysis of complex sounds can be carried out with a sound diffraction grating (Fig. XXVI. 4).

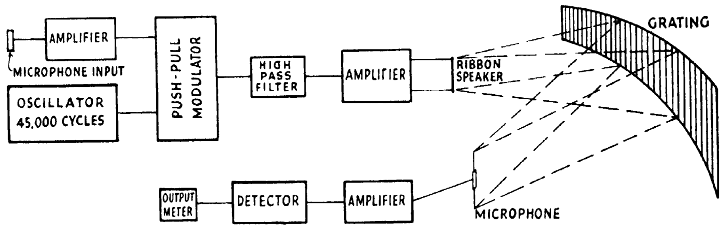


Fig. XXVI. 4. Grating spectroscope for analysing complex sounds.

Audible sound is received by a microphone, amplified and fed to a push-pull modulator which also receives the carrier frequency of 45,000 cycles per second. The lower side band is suppressed by a high-pass filter and the upper is amplified and fed to a ribbon loudspeaker designed to reproduce efficiently a range of frequencies from 45 to 50 kilocycles per second. This speaker will send out cylindrical waves since the width of the ribbon is comparable to the wavelength but its length is many times as great. The high frequency sound is directed on to the grating and diffraction occurs as for light. Single frequencies are spread out to form a spectrum. A small condenser microphone is moved through the spectrum and, by means of a suitable amplifier and output meter, measures the intensities of the high-frequency sound waves. An automatic recorder is arranged so that the motion of the microphone provides the abscissa and the output meter operates the ordinates. By using photographic recording, a sound spectrum can be established in one hundredth of a second.

Measurement of Loudness

It is necessary to distinguish between the intensity of a sound, as measured in terms of energy, and the loudness of a sound as judged subjectively by the ear. It is found that the degree of sensitivity of the ear varies throughout the frequency range and that the same mechanical energy put into sounds of different frequencies does not produce the same loudness to the ear. Where it is necessary to study loudness as opposed to intensity, a scale of equivalent loudness is employed. The equivalent loudness of a sound is defined (B.S.S. 661-1936) as the intensity level, relative to some accepted reference intensity, of a standard pure tone of specified frequency, which is judged to be as loud as the sound by a normal observer. The Phon is the unit of equivalent loudness and a sound is said to have an equivalent loudness of n phons if it is judged by a normal observer to be as loud as a 1,000 cycle/sec. pure tone of which the intensity is n decibels above a fixed zero of 10^{-16} watts per

sq. cm. This reference level is almost identical with the threshold of hearing.

Subjective Noise Meter. This is an instrument for determining the loudness of noise and operates on the principle used to define the Phon. An oscillator produces a tone of standard frequency the volume of which can be varied by an attenuator control. This tone is heard by the observer in a pair of earphones. To make a test the observer stands at the required point facing the source of sound. Quickly putting on the earphones, he estimates whether the standard tone is louder than the noise. Quickly removing them, he checks his estimate. The attenuator is adjusted and the process repeated until the operator judges the loudness of the noise and of the standard tone to be the same. The equivalent loudness of the noise is then indicated by the setting of the attenuator which is calibrated to read directly in phons. For accurate work readings should be taken by several observers to rule out personal defects of hearing.

Objective Noise Meter. The meter described above is more suited to the laboratory than to field work where instantaneous readings are desirable. To meet this need the Objective Noise meter has been developed consisting of a microphone, amplifier and output meter reading in phons. A frequency weighting network is incorporated to give the instrument a response similar to that of the ear. Unfortunately, this arrangement is not entirely satisfactory because, although correct readings can be obtained for pure tones of any frequency or amplitude, it has been found that for quiet and moderately loud noises with many component frequencies the readings may be considerably in error. For loud noises the accuracy is reasonable and the compactness and rapidity of use are of great advantage.

Tuning Fork Audiometer. Loudness measurements can be made very conveniently by observing the time taken for the noise to mask the decaying sound of a vibrating tuning fork. To ensure that the sound of the fork has a standard initial intensity it is struck by a spring hammer attached to its base. At the same moment a stop watch is started. The fork is held a standard distance from the ear and the watch is stopped at the moment when it ceases to be audible against the background of the noise to be measured. The fork can be calibrated against sources of standard loudness.

Measurement of Reverberation

Reverberation is the prolongation of sound in a closed space due to repeated reflection at the boundaries. It is considered to be the most important single factor in the application of acoustics to auditoriums. The reverberation period of an enclosure is the time which must elapse after the stopping of a steady note before the intensity of the sound in the enclosure falls to one millionth of its initial value, i.e. by 60 decibels. The unit of measurement is the second. This time is dependent on the volume of the enclosure, the total exposed area within the room and the average value of the absorption coefficients of the walls.

Subjective Method of Measurement. A source of sound of constant known intensity is set in operation in the room to be tested. When a steady state is reached an observer simultaneously stops the sound and

starts a stop-watch. The audible sound will decrease and, at the instant at which it becomes inaudible, the observer stops the watch. The output of the source is altered by a known amount and a second measurement is taken. If :—

L_1 = Output of sound source at first setting in decibels above a given reference level.

L_2 = Output of sound source at second setting in decibels above the same reference level.

t_1 = Stop-watch reading in seconds for first test.

t_2 = Stop-watch reading in seconds for second test.

Then the difference between t_1 and t_2 is the time required for the intensity of the reverberant sound to fall by $(L_1 - L_2)$ decibels. Hence :

$$\text{Reverberation Time} = 60 \frac{t_1 - t_2}{L_1 - L_2}$$

For accuracy several readings should be made.

Rotary Commutator Method. If a source of sound is started and stopped by a commutator, rotating at a constant speed, so designed that the source is "on" for a shorter time than it is "off," the peak intensity

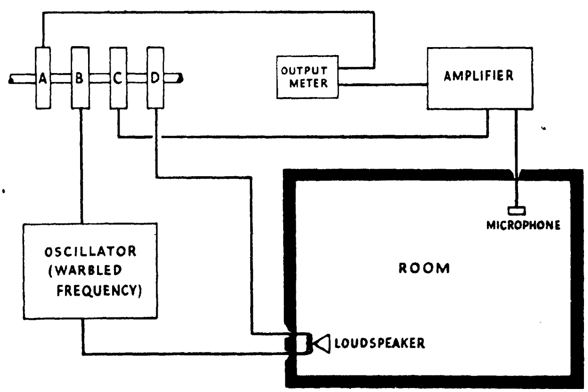


Fig. XXVI. 5. Measurement of reverberation time by rotary commutator.

at any point in the room will reach the same value at each cycle. After each stop the sound starts to decay and the reverberation time can be found if the intensities I_1, I_2, etc., at time t_1, t_2, after stopping the source, can be found. These values can be found with the aid of a special commutator. Four segments A, B. C, and D (Fig. XXVI. 5) are mounted on a shaft turning at a known speed. Segments B and D are designed so that a warbling note from an oscillator is reproduced by the loudspeaker during rather less than half of each revolution of the commutator shaft. The intensity of the decaying sound is measured by a microphone, amplifier and output meter circuit which is switched on at a given time by segments A and C. The position of the brush on A is variable so that the time elapsing, after the speaker is disconnected,

before the microphone is switched on can be altered. The time on the decay curve at which the output meter is connected is given by

$$t = \frac{\theta}{360} \cdot \frac{60}{n} \text{ secs.}$$

where t = Time after stopping sound source.
θ = Angular displacement of brush behind point at which speaker is disconnected.
n = Speed of shaft in revolutions per minute.

The reading of the output meter is taken for various settings of the brush, converted to decibels above some reference level and a graph is plotted showing the relative intensity at the microphone in decibels at various times after stopping the source. From the slope of this graph the reverberation time can be calculated.

Measurement of Absorption

Sound, striking a wall surface, may either be reflected, or absorbed by the wall or transmitted through the wall. In many cases absorption and transmission of sound are grouped together under the heading of total absorption, as in the case of an open window which is taken to have 100% absorption instead of 100% transmission.

Absorption is due to the transformation of acoustical energy into other forms in the material of the wall. The ratio of the sound energy absorbed by the material to the total energy falling upon it is called the absorption coefficient. The product of the absorption coefficient and the area of the absorbing surface in square feet is termed the absorption of the surface and is measured in "square foot units" or "Sabins."

Change of Intensity Method. If a constant source of sound is maintained in a room a steady state is reached for which it can be shown that

$$A = \frac{constant}{I}$$

where A = Total number of absorption units in the room.
I = Average intensity of sound.

The number of absorption units in the room will be equal to the total surface area multiplied by the absorption coefficient of the surface. Now if S square feet of the material to be tested is placed on the wall of the room the intensity of sound in the room will alter although the sound energy supplied by the source remains unchanged. If the introduction of the test material alters the number of absorption units in the room to A′ and the new intensity is I' then $\frac{A'}{A} = \frac{I}{I'}$ or $A' - A = (\frac{I}{I'} - 1)\, A$.

But if a is the absorption coefficient of the specimen and a' that of the wall covered by the specimen, $A' - A = S\,a - S\,a'$

Hence Absorption coefficient of Specimen $= a = \dfrac{(\frac{I}{I'} - 1)A}{S} + a'$

The sound source should be a warbling note of varying frequency to ensure thorough diffusion and to prevent the setting up of definite sound patterns in the room.

Comparison Method. In this method a special room is used having smooth concrete walls and a recess in one side about 4 feet wide and 6 feet deep, extending from floor to ceiling and closed by a movable timber shutter faced with polished steel plate. The recess is filled with absorbing material packed loosely near the shutter and more densely behind so that when uncovered it presents an almost perfect absorbing surface. The room contains a sound source, emitting a warbling tone of constant energy, and a microphone connected to an output meter measuring the intensity of sound in the room.

With the shutter closed a sample of material to be tested is introduced and the intensity of sound at the microphone is measured. On removing the sample the intensity of sound will be found to increase. The shutter is now raised, uncovering the 100% absorbing cavity, until the output meter reads the same as when the sample was in the room. Then sound absorbed by the sample is equal to the sound absorbed by the part of the cavity exposed and :

$$\text{Absorption coefficient of sample} = \frac{S_1}{S} \times 100\%$$

where S_1 = Area of 100% absorbing cavity uncovered.
S = Area of surface of specimen.

This method is accurate, rapid and simple and has the advantage that it is not necessary to know the characteristics of the room.

CHAPTER XXVII

CALCULATING MACHINES

From the earliest times men who have found it necessary to perform calculations have striven to invent machines to do their work for them. The ancient Roman merchant, with his sandtray and pebbles, known as an Abacus, was the forerunner of the modern scientific computer, with his all-electric calculating machine. The Abacus, in the form of a wire frame and beads, is still used throughout large areas in the Far East, and persists in this country as a piece of nursery school equipment or as a child's toy. The great progress that has been made in calculating machines only covers the last 300 years, for it was in 1642 that Pascal invented the first adding machine.

The fundamental necessity for any calculating machine is a means of transferring numbers from a setting mechanism to a series of adding wheels. In 1673 Liebnitz constructed a machine with the stepped-drum method of achieving this. Fig. XXVII. 1 illustrates this principle, which is still used in some machines. The stepped-drum is a cylinder having nine teeth running along its surface parallel to its axis. These teeth are of different lengths proportional to the numbers 1, 2, and so on, up to 9. To a square shaft running parallel to the drum is fixed a movable cogwheel, whose teeth engage those on the drum. According to the position of this cogwheel on the shaft when the machine is operated, the required number of teeth engage and rotate the adding wheel through the same number of places, thus adding the number to that previously shown. This apparatus is bulky, so in modern machines it has been modified and made more compact.

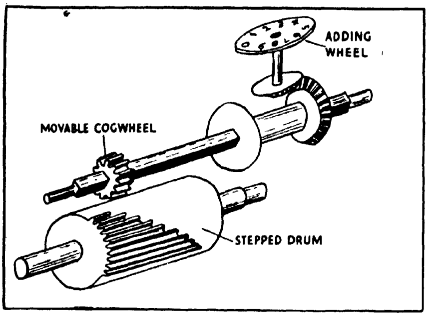


Fig. XXVII. 1. The stepped drum principle.

The other principal method used for the transfer of numbers is the pin-wheel, or Odhner wheel. The first machine involving this principle was constructed by Polini at Padua in 1709, and it has since been considerably improved. Most modern barrel-type machines involve this principle.

Fig. XXVII. 2 illustrates the essential feature, which is a wheel having nine teeth or pins that can be retracted. Each pin moves in a radial slot and has a stud on one side. This stud moves in a two-part race cut out of the setting lever. The radii of the two parts are

different and as the lever is moved the pins are projected or retracted. The pin-wheel is geared to a number wheel in the multiplier register (described below) and rotates it through the required number of places.

A calculating machine will perform the four arithmetical operations of addition, subtraction, multiplication and division, or any combination of these operations. While machines differ in operational detail, the more common ones are very similar in principle, so that a description of the fundamental operations as carried out on one machine can be taken as generally correct.

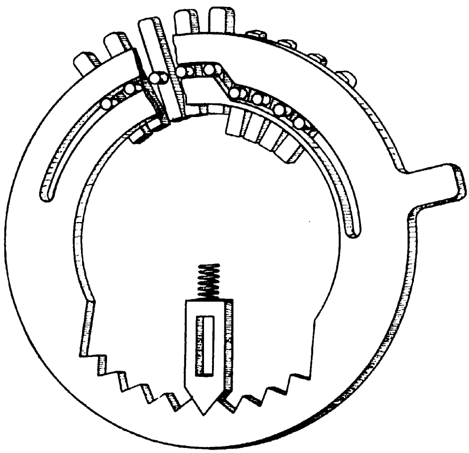


Fig. XXVII. 2. The pinwheel principle.*

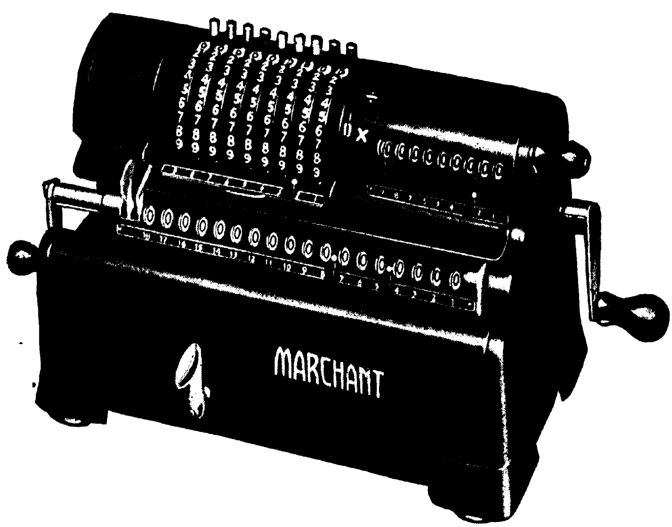


Fig. XXVII. 3. A typical hand-operated machine.

Hand-Operated Machines

Fig. XXVII. 3 illustrates a typical hand-operated machine. The first number to be dealt with is set by a series of setting levers and

recorded automatically on a sight dial above the levers; this enables it to be checked immediately. In front of the machine is the product register in which is recorded the result of the operation carried out on the number already set. A single forward turn of the operating handle adds this number once. Since multiplication is continued addition, multiplication by a given number is carried out by making the requisite number of turns of the handle. The number of turns is counted on the revolution counter, known as the multiplier register, on the right of the setting levers. The product register is mounted on a movable carriage; when this is moved one place to the right, multiplication is automatically by tens, as units results are entered into the tens place, and so on. (In the machine illustrated the product register is in its extreme right position, and would be moved eight places to the left before commencing multiplication). At the same time a pointer moves to the tens place in the multiplier register and the number of turns is recorded in that place. Thus multiplication by 342 is accomplished by two turns with the product register in the units position, four turns in the tens position, and three in the hundreds position, making nine turns in all. Subtraction is carried out by turning the operating handle in the reverse direction. This leads to a process known as "short cutting" in multiplication. Thus to multiply by 8, which would normally need 8 turns, it is quicker to multiply by 10 and subtract twice in the units position, making only 3 turns. Thus 3829 as a multiplier is considered as $4000 - 200 + 30 - 1$, making 10 turns instead of 22. The use of this device results in a time-saving of about 40 per cent.

There are three ways of doing division, of which the tear-down method is probably the most frequently used. In this method the dividend is set on the levers and transferred to the extreme left of the product register by a turn of the handle. The setting levers are cleared and the divisor set on them in such a position that its leading figure is aligned with the leading figure of the dividend, or with the second figure if the leading figure of the divisor is greater than that of the dividend. Subtractions are then made until the remainder is less than the divisor, when the product register is moved to the left, bringing another figure of the dividend into operation. It can easily be seen that this method corresponds exactly with the arithmetical process of long division. If a turn too many is made at any stage a bell rings and the mistake can be rectified by a turn in the opposite direction.

There are special features on some machines but space does not permit of a full list of them or of lengthy descriptions. The following are some of the more important:

(a) Zeroising devices, by which the registers can be cleared either separately or together.

(b) A device for transferring the number in the product register to the setting levers. By repeated use of this device the continued product of three or more numbers can be obtained. This is especially useful in obtaining powers higher than the second.

(c) A device for splitting the product register into two equal parts of which the right-hand part can be cleared without affecting the left-hand part. This enables a series of products to be seen individually on the right while their sum is accumulated on the

left. The first product is obtained in the usual way on the right and transferred to the setting levers. The product register is then moved to the extreme right and the product transferred to its left-hand section. The right half and the setting levers are then cleared, the product register is moved back to the extreme left and the machine is ready for the next product. This in its turn is added to the left-hand side and so the sum of the products is gradually built up.

For readers familiar with the identity $(A + B)^2 = A^2 + 2AB + B^2$ it may be noted here that, by considering the product register as divided into three parts and entering A on the left of the setting levers and B on the right (if A and B are reasonably small) and squaring, we get the results A^2, $2AB$ and B^2 in the three sections of the register. By repeating this for different values of A and B, and accumulating the results in the product register we can perform calculations of the type ΣA^2, $\Sigma 2AB$ and ΣB^2 which frequently occur in advanced analytical and statistical work.

Complements and Direct Numbers

If an operation is carried out that leads to a negative answer, the result is shown in the product register as the complement of the answer, i.e. the difference between the answer and a specified number. In any machine this specified number is one greater than the largest number that can be shown in the product register; thus in a machine having ten places in the product register it will be 9,999,999,999 + 1, or 10^{10}. The complement will be shown as a series of nines followed by other figures. If the subtraction 18 — 45 is performed the answer —27 will be shown in the register as 9999999973 or, in brief, . . . 973.

With practice it is easy to convert a complement to a direct number by mentally subtracting each digit, beginning from the left, from nine, and the last digit that is not zero from 10. Thus we have:

Complement	*Direct Number*
999954	46
993029	6971
994300	5700

Complements can also be converted to direct numbers by setting them on the setting levers and giving a backward turn to the handle.

Keyboard and Electric Machines

In many machines the setting levers are replaced by a keyboard in which each column has keys numbered 1 to 9. Another version has only 10 keys, numbered 0 to 9. In this machine keys representing successive digits are depressed in order, the setting register moving one place per figure as in a typewriter. This is an advantage in simple operations but renders the machine less flexible in more complex work.

Machines may be electrically operated. Fig. XXVII. 4 illustrates a machine of this type. In some, two numbers, whose product or quotient is required, are set up on separate halves of the keyboard and the desired operation is automatically carried out on the depression of a multiplication or division key. There is a variant in which the multiplier is set on the

Fig. XXVII. 4. An electric machine.

keyboard, which is then cleared by a special clearing key and the multiplicand is then set on the same keyboard. It is interesting to note that the multiplication of an eight-figure number by another eight-figure number takes about eight seconds.

A machine much used in advanced scientific calculation is the National accounting machine, which was really designed as a book-keeping machine. This has six separate adding registers, two of which will subtract as well as add. It is particularly useful for scientific work as numbers can be entered into any or all of the registers at one operation; they may also be transferred from one register to any combination of the remaining registers. Its principal applications have been to differencing and to integration from finite differences, including subtabulation.

There are various other specialised machines used by the scientific computer such as punched-card sorting and tabulating machines, and the differential analyser, for solving differential equations, but space does not permit of a description. Readers who are interested should refer to the books mentioned in the bibliography.

Scientific Applications

The use of calculating machines for scientific work has increased greatly in recent years. Extensive applications have been made by surveyors, astronomers, opticians, engineers and, of course, applied mathematicians. In addition to great saving of time and freedom from worry about the errors always liable to creep into "human" calculations, calculating machines are superior to logarithms in that they can be used for a greater variety of operations. It is possible to evaluate

expressions of the type Σab, Σa^2, $\Sigma(x + y)^2$ without noting intermediate results.

Multi-register machines like the National are also used for mechanical integration, and integrations from sixth finite differences may be performed. The combination of standard tables and machine forms a very powerful means of accurate calculation, as the machine provides a rapid means of interpolation ; new tables can be readily produced by this method. Great use has been made latterly of twin machines, in which two numbers may be set up and multiplied simultaneously by a common factor. This has been of particular service in the field of surveying, especially military surveying, with rectangular co-ordinates. Calculations of the type $R \sin \theta$ and $R \cos \theta$ can be readily evaluated in a single operation. These machines can be used also for simultaneous interpolation in sine and cosine tables.

There seems little doubt that the scientific investigator and research student of the future will depend to an ever-growing extent on machines for their calculations and that, in common with other historical occupations, the work of the arithmetician will become increasingly mechanised.

Slide Rules

The calculating machines so far described might be called the heavy artillery of the army of computers. The chapter would not be complete, however, without some reference to, and description of, the lighter and more mobile weapons at its disposal. Of these the slide rule is the most commonly known and the most frequently used.

Fundamentally a slide rule consists of two scales which can be moved one against the other. If these scales are linear the rule can be used

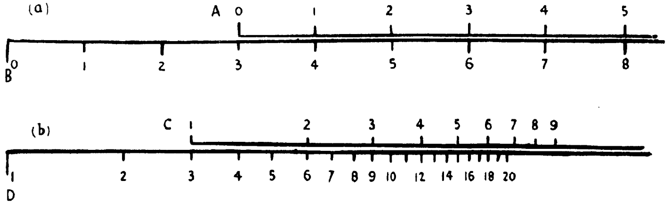


Fig. XXVII. 5. The slide rule principle. (a) with linear scales. (b) with logarithmic scales.

for the addition or subtraction of numbers. Thus, in Fig. XXVII. 5 (a), if we place the zero of scale A against the 3 on scale B, we observe that the 4 on scale A is against the 7 on scale B. This corresponds to the addition $3 + 4 = 7$, or to the subtraction $7 - 4 = 3$. If, however, as in Fig. XXVII. 5 (b), the scales are divided logarithmically (i.e. in the proportion of logarithms of the numbers) the operations carried out are respectively multiplication and division. Thus in this illustration if we set 1 (since $\log 1 = 0$) on scale C against 3 on scale D, we observe that 4 on scale C is against 12 on scale D. This corresponds either to the operation $\log 3 + \log 4 = \log 12$, i.e. $3 \times 4 = 12$ or to the operation $\log 12 - \log 4 = \log 3$, i.e. $12 \div 4 = 3$. It can easily be seen that operations like this can be readily extended to cover more complex

calculations, but it is not proposed to give a detailed description of further basic operations such as the obtaining of roots and powers, as these differ slightly on different makes of slide rule and full instructions are always provided by the makers. One point that may cause the beginner some difficulty is that the position of the decimal point is not given by the slide rule but has to be determined from the problem by observation. Slide rules may be relied on for at least three-figure accuracy, and frequently a fourth figure can be obtained.

Although the logarithmic scales are the basis of all slide rules, most types contain various other scales. Of these the most useful is the log-log scale, in which, as the name implies, the divisions of the scale are proportional to the logarithms of the logarithms of the numbers. This in conjunction with the ordinary logarithmic scale on the slide enables quick calculation of powers and roots where the indices are fractional. This operation corresponds to the following algebraic theory :

$$y = x^n$$
$$\therefore \log y = n. \log x$$
$$\therefore \log.\log y = \log n + \log.\log x$$

Other scales frequently found on slide rules are a reciprocal scale and scales of sine and tangent values. Specialised slide rules are made for surveyors, mechanical and electrical engineers and other professions. These have various scales and constants of particular significance marked on them. Fig. XXVII. 6 illustrates a slide-rule suitable for engineering and commercial calculations.

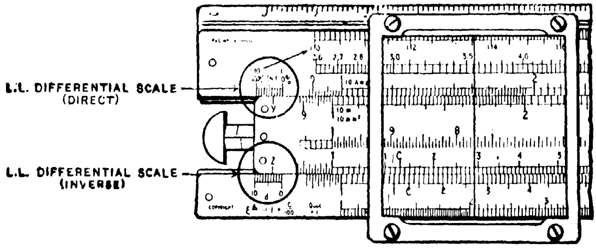


Fig. XXVII. 6. An engineer-commerce slide rule.

It should be further mentioned that slide rules are usually made of hard wood, faced with celluloid on which the scales are machine divided, and are provided with a glass cursor on which a fine line is etched to facilitate reading across from scale to scale.

A very convenient variant of the slide rule for carrying in the pocket is Fowler's Long Scale Calculator. This is very much like a watch in appearance. It consists of a circular metal case fitted at front and back with a glass cover. The main logarithmic scales are printed on two rotating dials, one on each face of the calculator. These are operated by thumb nuts on the outside of the case, similar to the winding nut on a watch. There is a fixed radial datum line marked on each glass cover, and the front dial also has a cursor in the form of a rotating radial line.

The scales already referred to are the "short" scales, and with their aid calculations of all types can be carried out to an accuracy of two or three significant figures. For greater accuracy—up to four figures—the "long" scale on the front dial is used. This consists of six concentric circles on the dial, forming the equivalent of a thirty-inch slide rule. On the back dial there are special scales for reciprocals, logarithms, square roots, log sines and log tangents.

There are other calculators similar in principle to slide rules in which the scales are mounted spirally on cylinders which move one inside the other. Fig. XXVII. 7a illustrates the Fuller Calculator, by the use of which an accuracy of at least five significant figures can easily be obtained and greater accuracy with practice. Although it is reasonably small to handle, the overall length being less than eighteen inches, the logarithmic scale mounted on the outer cylinder is 500 inches long, which, when compared with the 10-inch scale of the normal slide rule, explains the great degree of accuracy obtainable. Fig. XXVII. 7b shows the two index arms by means of which calculations are carried out, one being fixed and the other movable. As in the case with ordinary slide rules special models are obtainable having on the

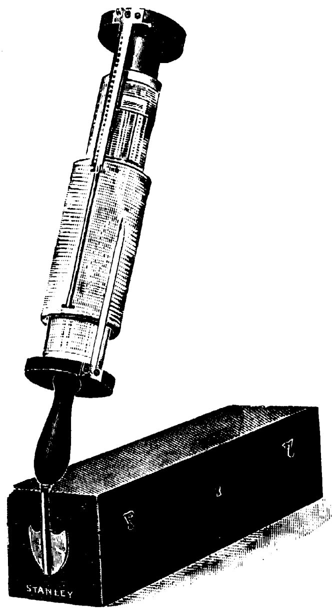


Fig. XXVII. 7a. The Fuller calculator.

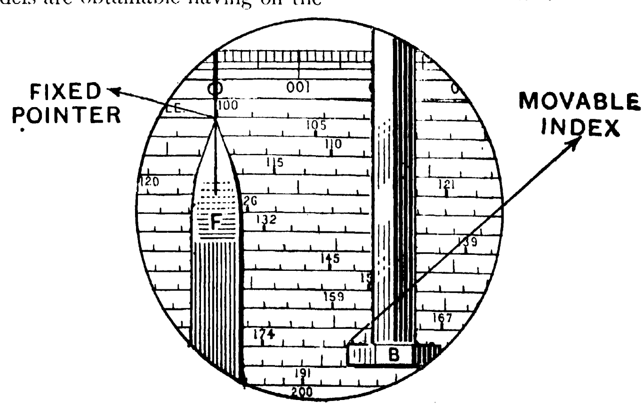


Fig. XXVII. 7b. Enlargement showing scale and pointers.

inner cylinders various scales making them particularly suitable for use by surveyors, engineers and so on.

The foregoing account, although necessarily brief, shows the wide range of aids to calculation available not only to the professional computer but to everyone whose work involves lengthy or tiresome arithmetical operation. They are not difficult to operate, nor do they involve a deep understanding of advanced mathematical theory, and their use will result in greater accuracy, increased speed, more confidence and very much less mental fatigue.

References

The Twin Marchant Calculating Machine and Its Application to Survey Problems. L. J. Comrie, M.A., Ph.D. Scientific Computing Service Ltd.

Mechanical Computing. Appendix I of the Second Edition of Clark's Plane and Geodetic Surveying. Volume 2, 1934. Constable & Co. Ltd.

Calculating Machines. Appendix 3 of L. R. Connor's Statistics in Theory and Practice. Sir Isaac Pitman & Sons, Ltd.

On the Application of the Brunsviga Twin 13z *Calculating Machine to Artillery Survey.* Scientific Computing Service Ltd.

Modern Machine Calculation. H. Sabielny. Scientific Computing Service Ltd.

The Office Machine Manual. Volume 2, No. 1, September, 1937.

Computing by Calculating Machines. The Accountant's Journal, May 1927.

Computing the National Almanac. Nautical Magazine, July 1933.

Scientific Applications of the National Accounting Machine. Supplement to The Journal of the Royal Statistical Society, 3, 87. (1936).

Application of the Hollerith Equipment to an Agricultural Investigation. Supplement to The Journal of the Royal Statistical Society, 4, 210. (1937).

CHAPTER XXVIII

HARDNESS INDICATORS

The property of a material termed hardness is generally used to indicate the resistance of the material to wear, which may incidentally infer that the material has strength, lack of brittleness, and the ability to withstand permanent deformation. Thus, a hardness test is applied to such articles as gear wheel teeth, cutting tools, the gauge surfaces of measuring instruments, shafts and spindles.

The amount of wear which takes place on a surface depends on a number of factors, such as the nature of the surface finish, the kind and surface finish of the material in contact with it, and the load intensity between the surfaces; but whatever its causes, wear is the rubbing or tearing away of small particles from a surface, which represents a form of permanent deformation. Thus the basis of most hardness tests is established, the principle being that a tool is made to deform the surface of the material being tested, the degree of deformation, taking into account the load on the tool, the shape of the tool, and the way in which it is applied to the surface, being used as an indication of the hardness of the surface.

Tests in which a measurement of the deformation is used to express the hardness are usually called indentation tests, the deforming tool being called the indenting tool. In such tests there must be no permanent deformation of the indenting tool.

Brinell Hardness Testing Machine

Hardness testing machines embodying the Brinell principle use a small hard steel ball as the indenting tool. This ball must have a certain minimum hardness, and must have a diameter of 10, 5, 2 or 1 mm. The indenting load is applied to the ball in a direction normal to the surface of the article being tested. The hardness of the material is given by a number, calculated by dividing the indenting load in kilogrammes by the surface area of the indentation in square millimetres. This number is called the Brinell Hardness number and is denoted by H_B. The H_B for a medium hard steel is about 250.

The size of the indentation will depend to some extent on the surface finish of the material being tested, the effect of surface finish being reduced as the size of the indentation is increased. The 1 mm. and 2 mm. diameter balls should be used only when the surface is polished to a degree obtainable with number 000 emery paper. The 5 mm. and 10 mm. diameter balls should be used only on a surface obtained by filing, grinding or smooth machining.

The indenting load is standardised in the following manner. The ratio $\frac{P}{D^2}$ where P is the load in kg. and D the diameter of the ball in mm. has the value 30 for hardness numbers above 160 (steels and cast iron), 10 for hardness numbers from 160 to 60 (copper alloys and aluminium

alloys), 5 for hardness numbers from 60 to 20 (copper and aluminium), and 1 for hardness numbers up to 20 (lead, tin and their alloys).

The load must be applied slowly and progressively, and the full load must be maintained for 15 seconds.

The surface area of the indentation is determined from a measurement of the diameter of the indentation and is calculated from the formula: area $= \frac{\pi D}{2} (D - \sqrt{D^2 - d^2})$ where D is the ball diameter and d the indentation diameter.

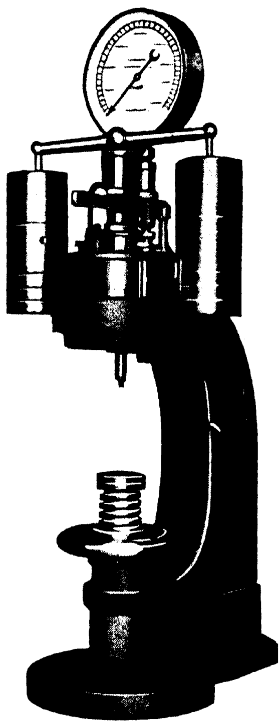


Fig. XXVIII.1. Standard Brinell hardness testing machine.

A typical Brinell hardness testing machine (Fig. XXVIII. 1) consists of a rigid stand fitted with a table on which the article to be tested is placed, and which is adjustable in a vertical direction by means of a hand wheel. At the top of the machine, and above the table, is situated an oil press into which oil is pumped by a hand lever, the piston projecting through the cylinder, and to the end of which is fitted the indenting ball. The pressure exerted on the piston is registered on a pressure gauge graduated in kg. force on the piston. The oil press is also provided with a dead weight controlling device, which acts as a check on the gauge, and prevents the required load from being exceeded. The dead weight will float when this load is reached. The table is elevated until the article being tested is in contact with the ball; the required load is then applied by the hand press lever. The article is taken from the machine and the indentation diameter measured by means of a microscope. The overall height of the machine is about two feet,and it is made to be mounted on a bench. There are many types of this machine made for special purposes such as the testing of large flat plates all over the surface, or for testing cylinders up to four feet in diameter.

Diamond Pyramid Hardness Testing Machine

There are certain factors in the Brinell test which make it unsuitable for the testing of very hard materials. The hardness of the ball itself limits its use in this respect, and also a shallow indentation is not very clearly defined at the edges, which makes the measurement of the indentation diameter inaccurate. The Vickers diamond pyramid hardness

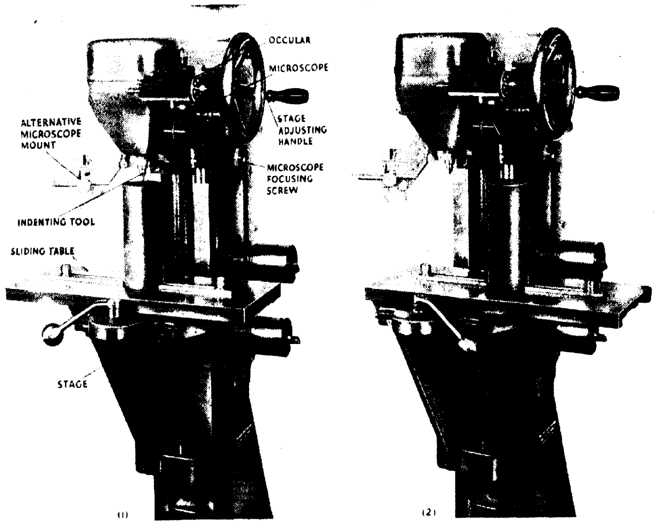


Fig. XXVIII. 2. Vickers diamond pyramid hardness testing machine. (1) The article being tested in position for making the impression. (2) The article in position for measuring the impression.

testing machine (Fig. XXVIII. 2) overcomes these difficulties by using a diamond indenting tool of pyramid shape, the plan view of the indentation thus being a square. The included angle between opposite faces of the pyramid is 136°. The hardness number, called the H_D, is determined by dividing the indenting load in kg. by the surface area of the impression in square mm.

The surface area of the indentation is calculated from a measurement of the length of the diagonal of the impression. A microscope is attached to the machine for this purpose, and a device called the ocular is incorporated in the eye-piece of the microscope. By the rotation of adjusting screws situated one at each side of the ocular, two shutters pass across the field of view of the microscope from the outsides to the middle, until each shutter coincides with a corner of the impression. The distance apart of the shutters then represents the diagonal length. A digit counter is geared to the adjusting screws and the ocular is calibrated so that one digit represents 0.001 mm. when a two-thirds objective lens is used in the microscope, and 0.0025 mm. when a one and one-half objective is used. The eye-piece and ocular can be rotated through 90° so that both diagonals can be measured, the average length being used in the determination of the H_D.

The load is applied through a lever mechanism with a load ratio of twenty to one. A foot pedal is depressed to wind up the loading mechanism, and a starting handle depressed by hand to apply the load. The

load is applied slowly and remains on the surface being tested for a period of time adjustable between ten and thirty seconds.

The article being tested is placed on a sliding table mounted on a vertically adjustable stage. The indentation is made with the sliding table in the extreme left position ; it is then moved to the extreme right position, the position of the microscope being such that the indentation is brought into the field of view. Alternatively, after making the indentation, the microscope, on a different mounting, can be swung round into position over the indentation. This avoids movement of the article being tested and is very useful for a large job.

By virtue of the fact that all impressions made with the diamond pyramid are geometrically similar irrespective of their depths, the ratio $\frac{\text{load}}{\text{area}}$ is constant for a given material for all load values, this not being so for a spherical indenting tool. A wide choice of loads is therefore allowable, and varies from 1 to 120 kg.

The machine is also supplied with 1 and 2 mm. diameter steel balls, which allows the Brinell test to be made. All the moving parts of the machine are covered and tables are supplied for the conversion of ocular numbers direct to hardness numbers.

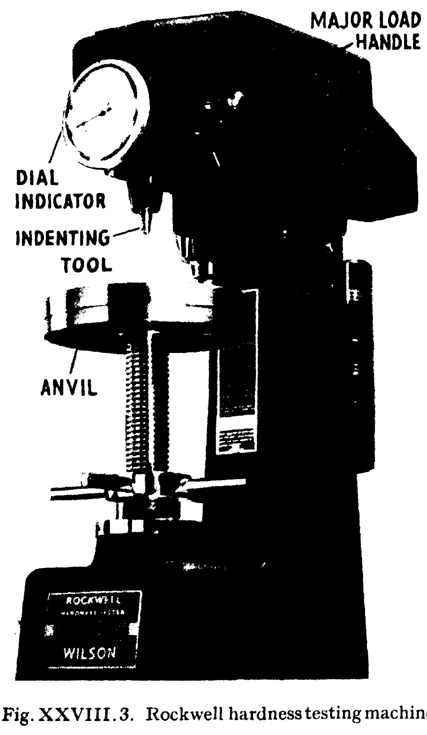


Fig. XXVIII.3. Rockwell hardness testing machine.

Rockwell Hardness Testing Machine

The majority of hardness testing machines depend on a measurement of the width of the indentation for the determination of the hardness number, and take no account of the effect of the surface finish of the article being tested beyond allowing a choice of load in order to produce an indentation large enough to reduce the effect of surface irregularity. The Rockwell test measures the depth of the indentation and uses it as an indication of the hardness ; it also takes into account the surface condition by eliminating, to a degree, its effect on the size of the indentation. The depth of the indentation bears a direct relationship to the vertical movement of the indenting tool, which is coupled to a dial

indicator, an instrument which shows small linear movements by a pointer on a circular dial. The effect of surface finish is reduced in the following manner. A small load, called the minor load, is applied to the indenting tool which makes a small indentation on the surface. The dial indicator pointer is then set to zero. A large load, called the major load, is then applied (in addition to the minor load), and the dial indicator registers a downward movement of the tool due to the application of the major load,which represents the increased depth of the indentation plus spring in the machine. The major load is now released, leaving the minor load on, the dial indicator now giving a reading which represents the depth of the permanent deformation due to the major load.

The dial indicator (Fig. XXVIII. 3) is marked with two scales, B and C. Scale B is used with a $\frac{1}{16}$ inch diameter steel ball for the indenting tool, and scale C is used with a diamond indenting tool, shaped conical with a rounded nose. The hardness number H_R is given by the dial indicator reading.

The minor load is applied by raising the anvil on which the test piece lies, so that the tool bears on the surface until the load is 10 kilogrammes, registered by a subsidiary pointer on the dial indicator. The major load, 90 kg. for the ball, and 140 kg. for the diamond, is applied by means of a dead weight and lever device, the rate of application being governed by an adjustable oil dashpot, and is applied by the movement of a crank handle. Reference blocks of standard hardness are supplied with the machine for the purpose of periodic checking.

Shore Scleroscope

In this instrument (Fig. XXVIII. 4) a falling hammer constitutes the indenting tool which provides the force to produce an indentation by virtue of its mass and acceleration. Thus, due to the nature of the indenting force, the test is called a dynamic test. The hammer is made of steel, is cylind-

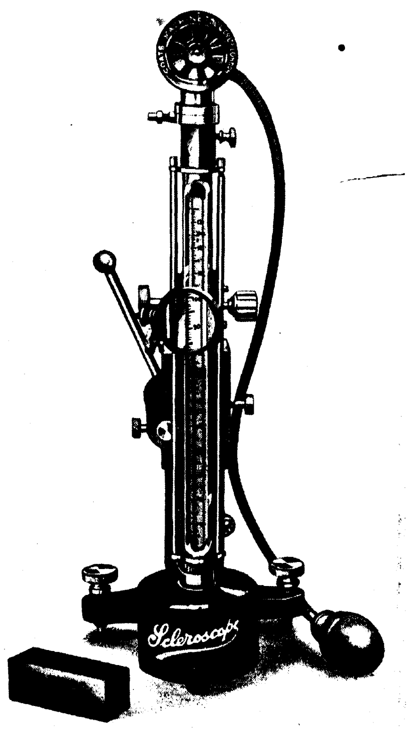


Fig. XXVIII. 4. Shore scleroscope.

rical in shape, about $\frac{3}{4}$ inch long and $\frac{1}{4}$ inch diameter and to the striking end is fixed a projecting blunt diamond. The hammer is drawn to the top of a vertical glass tube by means of a suction pump operated by a rubber hand bulb. The internal diameter of the tube is slightly greater than the hammer diameter, and is just over 10 in. long. The bulb is depressed and when released a suction is created in the tube which draws the hammer to the top where it is held by a mechanical catch. By depressing the bulb again an air valve is opened which allows free access of air to the tube when the hammer falls, the hammer catch releasing the hammer a fraction of a second after the bulb is depressed. The hammer falls a distance of 10 inches on to the surface of the article being tested, which is held in a clamp between the bottom of the tube and an anvil. The 10-inch length of tube, through which the hammer falls, is graduated into 140 equal divisions which are marked on a scale at the back of the tube. The scale number to which the top of the hammer rebounds is the scleroscope hardness number, denoted by H_S. The hammer is not held at the top of its rebound, hence the operator must exert considerable attention to note the height of rebound.

When operating the instrument an initial test should be made to note the approximate H_S. A magnifying glass which can be adjusted to any height in front of the tube, is then adjusted to the noted H_S and a second test made. The hammer top, this time, will appear in the field of view of the magnifying glass and the H_S can be read with greater accuracy. Before a test is made the instrument should be set level, with the glass tube vertical, by means of levelling screws in the base, the level being indicated by a plumb rod at the side of the tube. The instrument can be used on its clamp base for testing such articles as sheet metal, balls and pins; or on a swing bracket and post for odd-shaped articles which can be held in a separate vice.

Not more than one test should be made at any one point on a surface, for the reasons that a test deforms a surface, thus destroying its flatness, and that deforming the surface work-hardens it, thus giving a higher H_S for a subsequent test on the same spot.

Reference blocks of standard hardness are supplied with the instrument which are used for the purpose of checking and calibrating.

Herbert Pendulum Hardness Tester

This instrument (Fig. XXVIII. 5) consists of an inverted U-shaped metal body of 4 kg. weight, which can be supported in a state of balance on a 1 mm. diameter hard steel ball. The position of the centre of gravity of the instrument can be adjusted by means of a movable weight, the normal working position of the centre of gravity being 0.1 mm. below the centre of the ball. Thus the instrument constitutes a compound pendulum 0.1 mm. in length. Over the steel ball, on the top surface of the pendulum, a curved bubble tube and scale are mounted. The scale is graduated into one hundred divisions, the 50 division being vertically above the point of suspension.

There are a number of different forms of hardness test which can be made with the pendulum. The time hardness test is carried out by resting the pendulum on the surface being tested, and oscillating it through a small arc, the time for ten single swings, measured with a

stop watch, being the time hardness number. Time hardness numbers for common materials are, glass 100, hard carbon steel 65, mild steel 20, and lead 3. This test can also be used as an indication of the work-hardening capacity of a material, i.e. the degree of hardness induced in a material by the application of work producing deformation. A time hardness test is made, the surface is then work-hardened by rolling it with the pendulum, making two complete passes, and another time hardness test made. This process is repeated until a maximum time hardness number is reached and passed. The number of passes required to reach the maximum time hardness number and the difference between the initial and maximum time hardness numbers being indications of the work hardening capacity of the material.

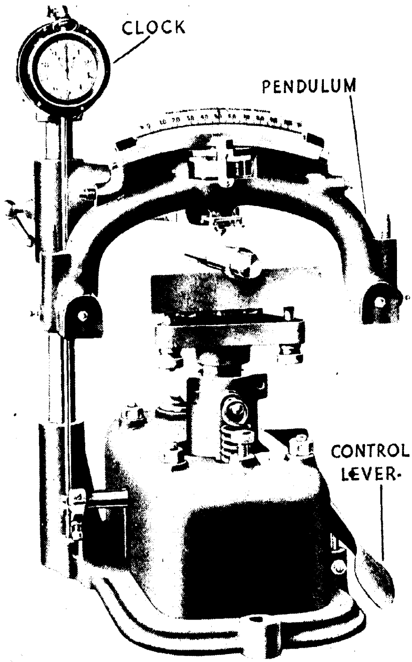


Fig. XXVIII. 5. Pendulum operating stand. The release of the pendulum and the timing are mechanically controlled.

The scale test is made by placing the pendulum on the surface and tilting it so that the bubble registers 0 on the scale. The pendulum is released and the length of swing registered by the bubble reading at the other end of the swing is called the scale hardness number. Scale hardness numbers do not correspond with time hardness numbers and can be taken as an indication of the resistance of the material to rolling.

The hard steel ball can be replaced by a 1 mm. diameter spherical-tipped diamond for the testing of hot and very hard materials.

Edgewick Visual Hardness Testing Machine

This machine applies an indentation test and steel balls or diamond pyramid can be used for the indenting tool. The positioning of the article being tested, the application and release of the load, and adjustment of the time of contact between indentor and surface are made very simple. The outstanding feature of the machine is the method of measurement of the indentation. When the indentation has been made the indenting tool springs out of the way, leaving the indentation in the field of view of a projection apparatus, and an image of the indentation

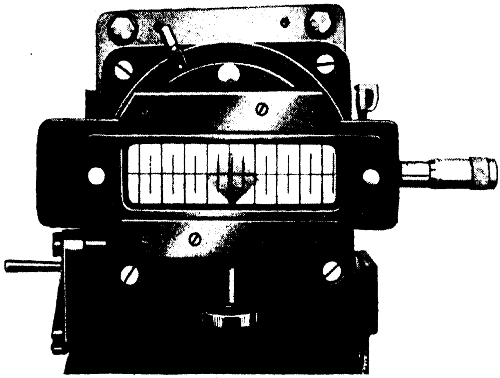


Fig. XXVIII. 6. Edgewick visual hardness tester. Showing a diamond impression projected on to the measuring screen.

is projected on to a screen fitted at the front of the machine (Fig. XXVIII. 6). The image is magnified 70 times. A scale is imposed on the screen which enables a direct reading in tenths and hundredths of a millimetre to be made, whilst a micrometer adjustment makes reading possible to one-thousandth of a millimetre. For production work the screen can be marked with tolerance lines. The measurement of the indentation is thus made very simple, and eliminates the possibility of eye-strain due to the continual use of a microscope.

CHAPTER XXIX

VACUUM TUBES AND THERMIONIC VALVES

A thermionic vacuum tube is a highly-exhausted tube, usually of glass, containing a heated electrode, the cathode, which emits electrons, and other electrodes to control or collect the emitted electrons. Electrons carry a negative charge and may be attracted to a metal plate (or anode) if this is positive to the cathode. The flow of negative electrons from the cathode to the anode constitutes an electric current from anode to cathode.

The emission of electrons leaves the cathode positively charged so that, if there are no other positively charged electrodes in the tube, the emitted electrons experience a retarding force acting towards the cathode, and eventually fall back into it. At any instant the space outside the cathode contains a number of electrons, some moving away from the cathode, some towards it, others stationary. These electrons form a negative "space charge" which together with the cathode produce an electric field directing electrons towards the cathode.

Cathode Materials

The choice of emitter is restricted; the material used must be such that it may be operated at a temperature at which the electron emission is reasonably copious, without excessive evaporation. The emitter used is usually tungsten, thoriated tungsten, or a mixture of barium and strontium oxides.

Tungsten is operated at white heat (about 2100° C.) and, because of the heat radiation at this temperature, requires a comparatively large heating power; about 1 watt of heating power enables the cathode to emit 2 milliamps (or 1.25×10^{16} electrons per second). Tungsten filaments are used in high power tubes because of their robustness and ability to withstand overloads.

Thoriated tungsten filaments are made of tungsten mixed with one or two per cent of thorium oxide. They are "activated" before being put into service by operation at a temperature of about 2400° C. for one or two minutes, and then at about 1900° C. for fifteen or twenty minutes; in use they are operated at about 1600°C. The activating process causes the filament surface to be coated with a layer of thorium one molecule thick. Such filaments give an emission of about 40 milliamps per watt of heating power.

Oxide-coated cathodes may be directly or indirectly heated. If the former the filament is usually of nickel coated with the oxide layer. If the latter the cathode is in the form of a hollow nickel cylinder, insulated with a refractory material such as alumina or magnesia, and placed within the cathode. These cathodes are activated by operation at about 1000° C. The actual emitting surface appears to be a monomolecular layer of barium and strontium, very easily contaminated by oxygen. In practice, therefore, tubes using oxide-coated cathodes are "gettered," that is, a small piece of magnesium is evaporated inside the valve after

the pumping and sealing process is completed. The gettering is done while the electrodes are heated to drive out occluded gases, and the magnesium combines with any oxygen present, then condenses as a silvered patch on the glass. Such cathodes are usually operated with a surface temperature of about 800° C.; the emission may be from 50 to 250 milliamps per watt of heating power.

The Diode

A diode (two electrode valve) contains a cathode surrounded by a metal plate (the anode), mounted on stout support wires which are sealed into the glass envelope. The characteristics of the diode may be considered as fundamental for all types of thermionic vacuum tubes.

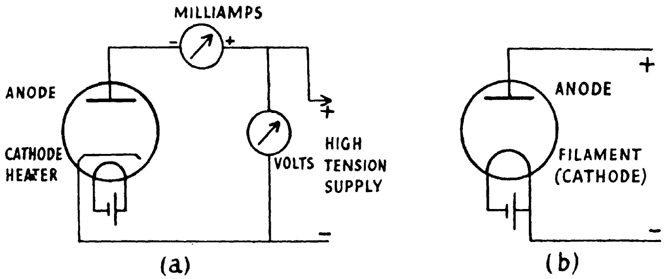


Fig. XXIX. 1. (a) Circuit for measuring the anode characteristic of an indirectly heated diode. (b) Connection of diode with directly heated cathode.

The important characteristic of a diode is the relationship between the anode to cathode potential difference, and the anode current (Fig. XXIX. 1). The curve showing this relationship is known as the static anode-current anode-voltage (Ia—Ea) characteristic (Fig. XXIX. 2). The shape of the curve may be accounted for as follows: electrons leaving the cathode come under the influence of the combined electric field due to the anode/cathode field and the cathode/space-charge field. If the anode is at the cathode potential, most of the electrons return to the cathode; only electrons emitted with very high velocity reach the anode. Electrons reaching the anode return to the cathode via the external anode to cathode circuit and the anode current meter registers a tiny current.

If the anode is made positive more electrons reach it and the space charge decreases. An increase in the anode to cathode field is accompanied by a decrease in the cathode to space charge field and the increase in anode current is disproportionately large. This state persists throughout the whole of the lower, curved, portion of the characteristic.

At anode voltages of 30 or 40 volts all emitted electrons travel straight from anode to cathode, the space charge practically disappears as the electrons remain in the space for a negligible time, and the current flow is entirely determined by the emissivity of the cathode; this current flow is the total emission or saturation current of the cathode and can only be increased by raising the cathode temperature.

Oxide-coated cathodes do not show a normal saturation effect. An increase of anode current apparently causes more barium to be diffused from the oxide to the emitting surface and raises the emission. The dotted line of Fig. XXIX. 2 shows the effect produced. Operation at more than about half "saturation" current rapidly ruins an oxide-coated cathode.

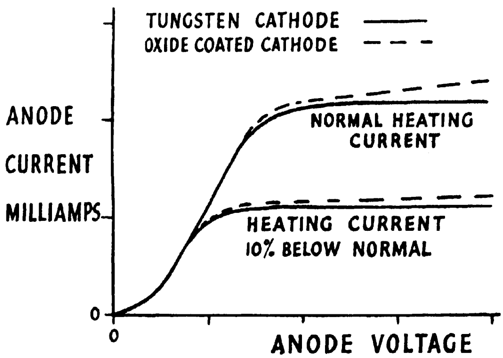


Fig. XXIX. 2. Typical anode current-anode voltage characteristics. All thermionic vacuum valves have anode characteristics of a similar shape.

As the anode to cathode voltage is raised the effect of the limited emission begins to appear and the characteristic becomes almost straight before bending over to the saturation current.

A.C. Anode Resistance. The resistance of a diode is indefinite; it varies with the operating conditions. The "differential" A.C. anode resistance, or more simply the A.C. anode resistance (R_a), i.e. the ratio "change of anode voltage divided by change of anode current produced," is constant over the straight portion of the characteristic and is often specified.

Diodes are used as rectifiers, and are made in many sizes for various uses. For power rectification high voltages and currents may be handled, and large area anodes are necessary to dissipate the heat produced by bombardment by fast-moving electrons.

The Triode

The three electrode tube or triode valve contains a helix of spaced wires, known as the control grid, between the cathode and the anode. This grid is normally used to control the anode current, and in most cases is kept negative to cathode so that no electrons flow to it.

The electric field near the cathode depends on the anode-cathode field and on the grid-cathode field, so that the anode current can be varied either by a change of anode-cathode voltage or by a change of control grid potential.

Amplification Factor. The grid-cathode field may be many times as great as the anode-cathode field for the same voltage between the electrode

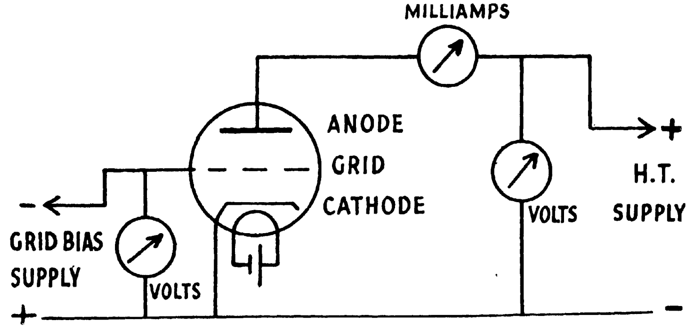


Fig. XXIX. 3. Circuit for measuring triode characteristics.

and cathode. The ratio, grid to cathode field divided by anode to cathode field, for the same electrode voltage (or the ratio grid-cathode capacity divided by anode-grid capacity) is known as the "amplification factor" (μ) of the tube. If the anode voltage is raised by V_1 volts and the grid then made V_2 volts more negative so that the anode current returns to its original value, then $\frac{V_1}{V_2} = \mu$

Mutual Conductance. The ratio change of anode current divided by change of grid voltage which produces it is known as the mutual conductance (g_m) of the tube. If the grid voltage is changed by V_2 volts, the anode voltage remaining unaltered, then the anode current will change by $V_2 g_m$ amperes; but a change of V_2 volts between grid and cathode is equivalent to a change of μV_2 volts between anode and cathode; thus the anode current must change by $\frac{\mu V_2}{R_a}$ amps. Hence $g_m R_a = \mu$.

g_m is usually expressed in milliamps per volt.

Triode Characteristic Curve. For a triode a family of curves may be constructed. Fig. XXIX. 3 shows the circuit and Fig. XXIX. 4 the

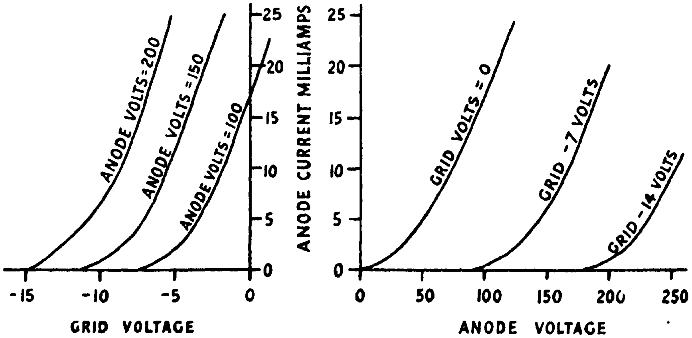


Fig. XXIX. 4. Typical triode characteristics. The valve to which these curves refer has an anode resistance of 4000 ohms, a mutual conductance of 4mA.volt and an amplification factor of 16.

shapes of typical E_g—Ia and Ea—Ia characteristics. The constants g_m and Ra may be found from the slopes of these characteristics.

The triode is mainly used to amplify alternating voltages. The circuit of a triode amplifier using a resistance as an anode load is shown in Fig. XXIX. 5. When the grid is made more negative the anode

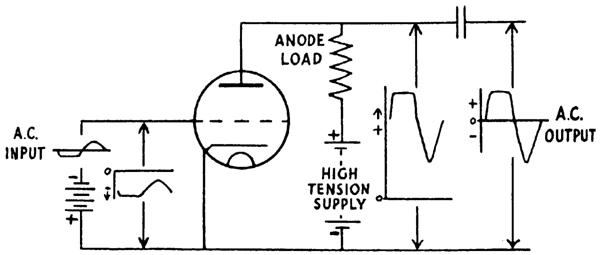


Fig. XXIX.5. Circuit of resistance-capacity coupled amplifying stage. The condenser "blocks" the D.C. component of the anode to cathode voltage.

current falls, the potential drop in the anode load reduces, and the anode to cathode voltage rises. The alternating anode to cathode voltage is a magnified inverted copy of the alternating grid-cathode voltage.

Triodes are made with amplification factors of between four and one hundred, and A.C. anode resistances between 800 and 60,000 ohms. Valves intended to deliver A.C. power, for example to operate a loudspeaker, have low values of μ and Ra.

Triodes are mainly employed as amplifiers at between 20 and 20,000 cps. At higher frequencies coupling from the anode to grid by the capacity between them modifies the performance considerably.

Screen Grid Valves, Pentodes and Kinkless Tetrodes

In these valves a second grid, the screen grid, is introduced between anode and "control" grid. This electrode is maintained at a steady potential relative to the cathode and acts as an electrostatic screen, preventing changes in the anode potential from having any influence on the control grid. The effective anode to grid capacity is reduced to a thousandth or less of its value in a triode.

The screen prevents the anode from having much influence in the cathode to screen space, and the screen itself is maintained positive to cathode to draw electrons from it. Many of the electrons shoot through the spaces between the screen wires into the anode to screen space. If the anode is at zero potential a retarding field acts in the screen-cathode space, due partly to the screen-anode field and partly to the presence of a space charge. In this case most of the electrons are brought to rest before reaching the anode, and then fall back to the screen, so that the anode current is small and the screen current comparatively large.

If the anode is made 20 or 30 volts positive to cathode the anode current increases considerably, the space charge in the screen-anode space disappears and practically every electron passing the screen reaches

the anode. A further increase in anode voltage has little effect on the anode current owing to the presence of the screen. The characteristics to be expected from a tetrode (four electrode valve) are illustrated in

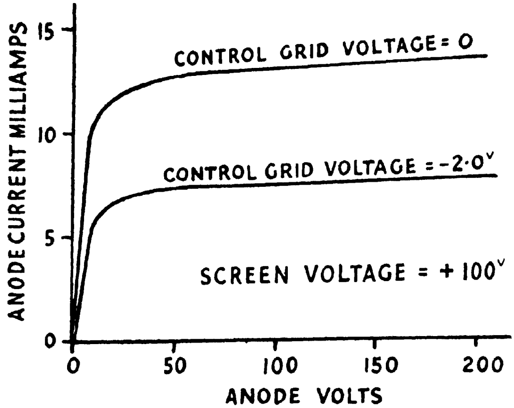


Fig. XXIX. 6. Typical anode characteristics of a pentode or kinkless tetrode.

Fig. XXIX. 6. The working portion of the characteristic is with the anode voltage exceeding about 50^{V} and in this region the effect of the anode potential on the anode current is very small, so that the A.C. anode resistance is high and the amplification factor is also high.

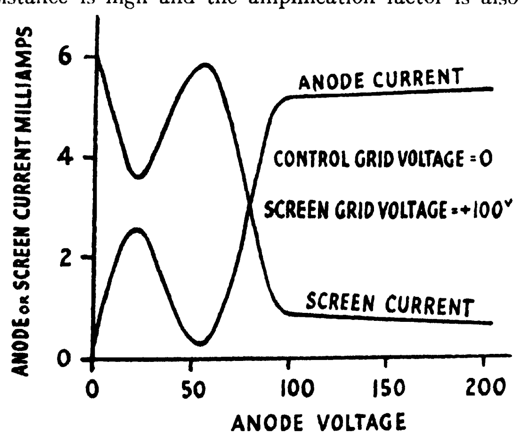


Fig. XXIX. 7. Typical characteristics of a screen grid valve, showing the "kink" caused by secondary electron emission.

Simple screen grid valves exhibit a more complex characteristic of the type illustrated in Fig. XXIX. 7 ; the characteristic is kinked in the region anode volts = 30^{V} to anode volts = screen volts. This effect is due to secondary electron emission.

When an electron having a kinetic energy of more than about 25 electron volts (4×10^{-11} ergs) hits an atom, electrons of lower energy may be emitted from the atom. The greater the energy of the primary electrons, the more numerous the secondary electrons emitted.

In the screen grid valve secondary emission takes place at the anode when the anode to cathode potential reaches 25 volts. A further increase in the anode voltage is accompanied by a small increase in the number of primary electrons reaching it per second, and a larger increase in the number of secondary electrons emitted per second. As long as the screen is positive to anode the electric field between them pulls electrons towards the screen. Secondary electrons emitted from the anode are returned to the screen by the field, and an increase of anode voltage is accompanied by a net decrease in anode current, the screen current rising accordingly.

When the anode potential approaches the screen potential some of the secondary electrons fall back to the anode. If the anode is positive to the screen all the secondary electrons return to the anode, and the anode and screen currents have their normal values.

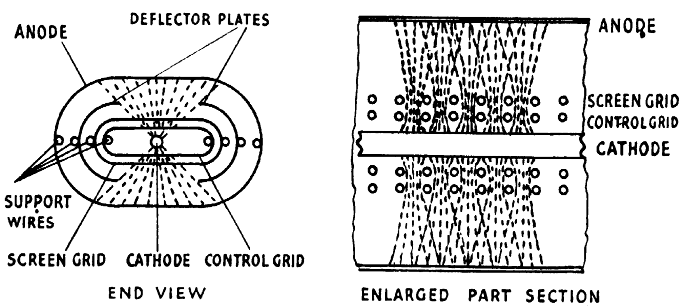


Fig. XXIX. 8. Construction of a kinkless tetrode (beam tetrode). The dotted lines indicate electron paths.

The Pentode (*Five Electrode Valve*). One means of avoiding the kink in the characteristic is the introduction of a "suppressor" grid between anode and screen. This is connected to the cathode and ensures that the electric field outside the anode acts from anode to suppressor, thus directing electrons towards the anode.

The Kinkless Tetrode. This is constructed so that a space charge is produced in the anode to screen space even with anode voltages as high as the screen voltage. The desired effect can only be achieved with exact electrode spacings and, as these spacings cannot be preserved in the neighbourhood of the support wires, the electron stream near these wires is cut out by deflector plates connected to the cathode. Fig. XXIX. 8 shows the construction of a kinkless tetrode.

Pentodes and kinkless tetrodes have amplification factors of from 500 to 2000 and anode resistances of from 60,000 ohms to 2 megohms. They may be used to give high amplification at audio frequencies or for radio frequency amplification.

The Cathode Ray Tube

In the cathode ray tube a stream of electrons impinges upon a screen which then fluoresces and emits visible light. The stream is focused on to a spot on the screen and may be deflected by electric or magnetic fields from side to side and up and down. It is particularly useful for the examination of rapidly-changing voltages or currents since the electron beam has almost no inertia.

The screen is made of a thin opalescent layer of a salt such as calcium tungstate, zinc phosphate, zinc orthosilicate, etc. These materials all exhibit the property of fluorescence when struck with a fast-moving charged particle. Some materials have a long "afterglow," that is, the glow on the screen persists for as much as one-tenth of a second after the electron bombardment ceases ; others have an afterglow of less than one microsecond. The colour of the light depends on the salt used ; green, blue, bluish-white are usual.

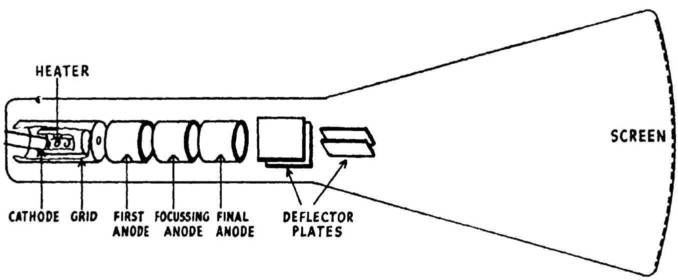


Fig. XXIX. 9. Arrangement of electrodes in an "electrostatic" cathode ray tube.

The "Electrostatic" Tube. The type of tube most often used is illustrated in Fig. XXIX. 9 ; this type uses electric fields to focus and deflect the electron stream. Electrons emitted from the cathode are attracted towards the final anode which is maintained from 500 to 5,000 volts positive to cathode. The "grid" surrounding the cathode is made negative to it and repels the electrons, some of which escape through a fine hole to form a "point source" of electrons just outside. The number of electrons escaping and the brightness of the spot on the screen, are controlled by the grid potential.

The electrons are attracted down the tube towards the final anode and pass through the system of cylindrical anodes ; the electric fields between these anodes are illustrated in Fig. XXIX. 10. In passing from one anode to the next, each electron is accelerated along the tube and is also first accelerated inward, then outward, except for electrons which move along the axis of the tube and are not deflected from that path. If the cylinders are the same diameter the inward and outward acceleration are equal, but, as the electron velocity is greater in the second part of the field, the inward acceleration is effective for a greater time, so that in passing from a point inside one anode to a point inside the next each electron is given an extra inward velocity.

The radial field is strongest just inside the surface of the cylinders and zero at the centre, so that electrons which diverge most strongly from the point source pass into the strongest radial field and receive the greatest inward velocity. In passing through the field the electron stream is made to diverge less strongly, or even to converge ; the same effect occurs between each pair of anodes, and by suitable choice of potentials the stream may be focused to a spot on the end of the tube (Fig. XXIX. 10). In some tubes only two anodes are used.

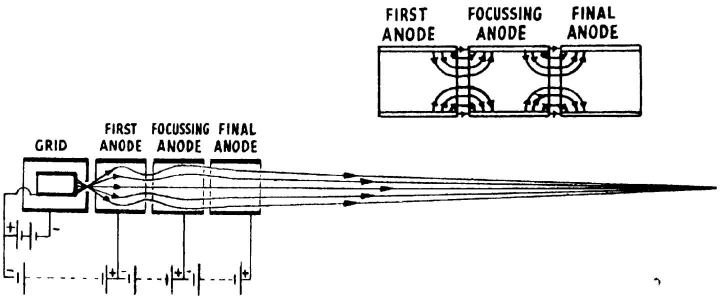


Fig. XXIX. 10. Electrostatic focusing. The upper figure shows the electric fields between the anodes ; the arrows show the direction in which an electron is urged (i.e., the reverse of the conventional field direction). The lower figure shows the paths followed by electrons from the cathode to the screen.

The screen is connected to the final anode either by a graphite coating on the inside of the glass or by surface leakage over the glass. Electrons accelerate up to the final anode, then move with constant velocity from the anode to the screen, passing the deflector plates on the way. A potential difference applied between the deflector plates produces an electric field perpendicular to the tube axis. Electrons in this field are accelerated towards the positive plate and in passing the plates acquire a transverse velocity, so that the electron beam as a whole is bent and the spot on the screen deflected by an amount proportional to the deflecting potential difference. A second pair of plates at right angles to the first makes horizontal and vertical deflection possible.

The "Magnetic" Tube. The type of tube illustrated in Fig. XXIX. 11 uses magnetic fields to focus and to deflect the electron stream. An electron moving at right angles to a magnetic field experiences a force perpendicular to its direction of motion and perpendicular to the direction of the field. If emitted in a uniform field, in a direction perpendicular to the field, an electron moves in a circle, the radius of which is proportional to its speed ; the time taken to describe this circle is independent of the velocity of the electron and inversely proportional to the strength of the magnetic field. An electron moving along a magnetic field experiences no force.

If the electron moves at an angle to a magnetic field its velocity may be resolved into two components. The component along the field is unaltered ; the component at right angles to the field is converted

into a circular motion, and the resultant path is a helix; this fact is used in magnetic focusing.

The cathode and grid assembly produce a point source of electrons; electrons leaving the point source have practically the same axial

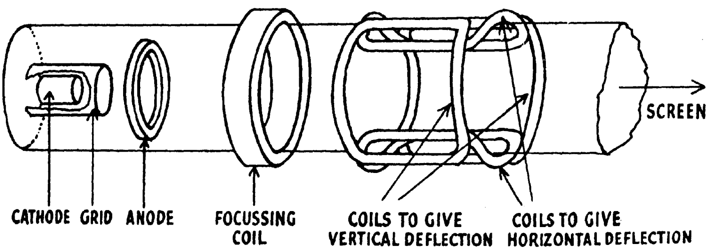


Fig. XXIX. 11. Arrangement of a cathode ray tube using magnetic focusing and deflection.

velocity, and therefore take the same time to travel down the tube to the screen. The tube is placed in an axial magnetic field, whose strength is adjusted so that the time taken by an electron to describe a circle in it is the same as that taken by the electron to travel the length of the tube. Every electron leaving the point source describes a helix and arrives back on the axis after completing one turn. As each turn is completed in the same time, that is, the time taken for the journey to the screen, each electron arrives back on the axis at the instant that it hits the screen, and the electron stream is focused to a fine spot (Fig. XXIX. 12). The same result is obtained with a focusing field of greater

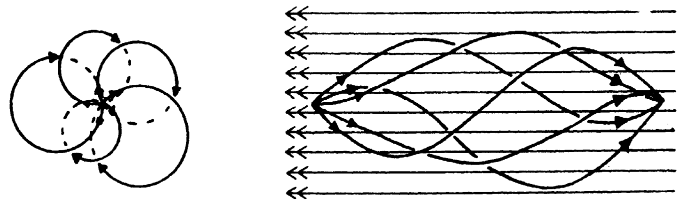


Fig. XXIX. 12. Magnetic focusing. Showing the paths followed by electrons from a point source to screen; five electrons are shown leaving the point source in different directions with different radial velocities. Double-headed arrows indicate the magnetic field.

strength, so that each electron completes several turns of the helix. It can be shown that a uniform field is not essential and a short coil carrying a current may be used instead.

Horizontal or vertical deflection is obtained by means of vertical or horizontal magnetic field. The deflecting field is provided by a current flow in coils with axes perpendicular to the tube axis. In passing through the field the electron beam is bent through an angle proportional to the current in the deflecting coils.

The X-Ray Tube

X-rays are waves of the same nature as light but of shorter wavelength and greater penetrating power; the shorter the wavelength, the greater its penetrating power. They are produced when a fast-moving charged particle is stopped suddenly. Some of the kinetic energy lost is radiated in the form of a pulse of X-rays; most of the energy is radiated in a direction at right angles to the direction of motion of the particle.

The radiation is of many wavelengths and the intensity distribution depends partly upon the material of the target. With a given target the wavelength of maximum intensity becomes shorter as the particle velocity is increased; the shortest wavelength radiated is inversely proportional to the energy of the particle (about 0.63×10^{-8} cm. with a kinetic energy of 20,000 electron volts). The efficiency of the conversion process is low; usually only about one-thousandth of the energy dissipated at the target appears as X-radiation. Efficiency increases with the atomic number of the target, and tungsten targets are usually employed because of the high atomic number and high melting point of tungsten.

Early forms of X-ray tubes, and some modern types, contain gas at a low pressure, and the discharge is conducted by ions of the gas; such tubes are not strictly thermionic vacuum tubes. Most modern tubes use a heated tungsten filament as a source of electrons and the tubes are evacuated. The filament is surrounded by a metal cylinder serving to focus the electron beam into a fine pencil (Fig. XXIX. 13). The electrons are accelerated to the anode by an anode to cathode potential difference of many thousand volts. The cathode always supplies its total emission, and the current through the tube, and the intensity of the X-radiation may be controlled by adjustment of the filament current.

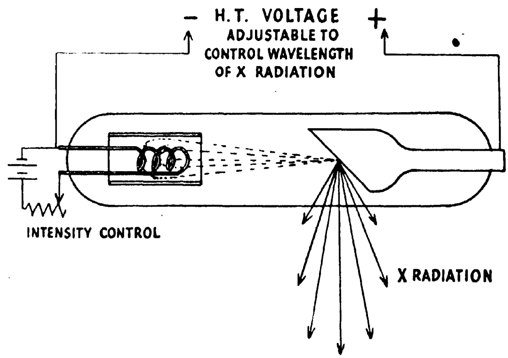


Fig. XXIX. 13. Arrangement of electrodes in an X-ray tube.

References

Thermionic Emission. T. C. Jones. Methuen.
Thermionic Vacuum Tubes. Appleton. Methuen.
Ions, Electrons and Ionizing Radiations. Crowther. Arnold.
Time Bases. Puckle. Chapman & Hall.
Industrial Radiology. Crowther. Arnold.
Radio Engineering. Terman. McGraw Hill.